Linux Kernel Module Programming

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USB Driver

What is USB?

- USB stands for Universal Serial Bus
- Provides an expandable, fast, bi-directional, low cost, hot pluggable Plug and Play serial hardware interface
- Allows users to connect a wide variety of peripherals to a computer and have them automatically configured and ready to use
- Implemented to provide a replacement for legacy ports to make the addition of peripheral devices quick and easy for the end user

Pre-Releases of USB

- **USB 0.7:** Released in November 1994.
- **USB 0.8:** Released in December 1994.
- **USB 0.9:** Released in April 1995.
- **USB 0.99:** Released in August 1995.
- **USB 1.0:** Released in November 1995

History of USB

- There have been three versions released prior to 3.0
  - USB 1.0 in January 1996 – data rates of 1.5 Mbps up to 12 Mbps
  - USB 1.1 in September 1998 – first widely used version of USB
  - USB 2.0 in April 2000

    Major feature revision was the addition of a high speed transfer rate of 480 Mbps

USB 3.0 Now

- On Nov 17,2008 It was Developed
- It is called as “SUPER SPEED” Technology
- Transfer Mode of Up to 4.8 Gbps

Key Features

- Single connector type
  - Replaces all different legacy connectors with one well-defined standardized USB connector for all USB peripheral devices
- Hot swappable
  - Devices can be safely plugged and unplugged as needed while the computer is running (no need to reboot)
- Plug and Play
  - OS software automatically identifies, configures, and loads the appropriate driver when connection is made

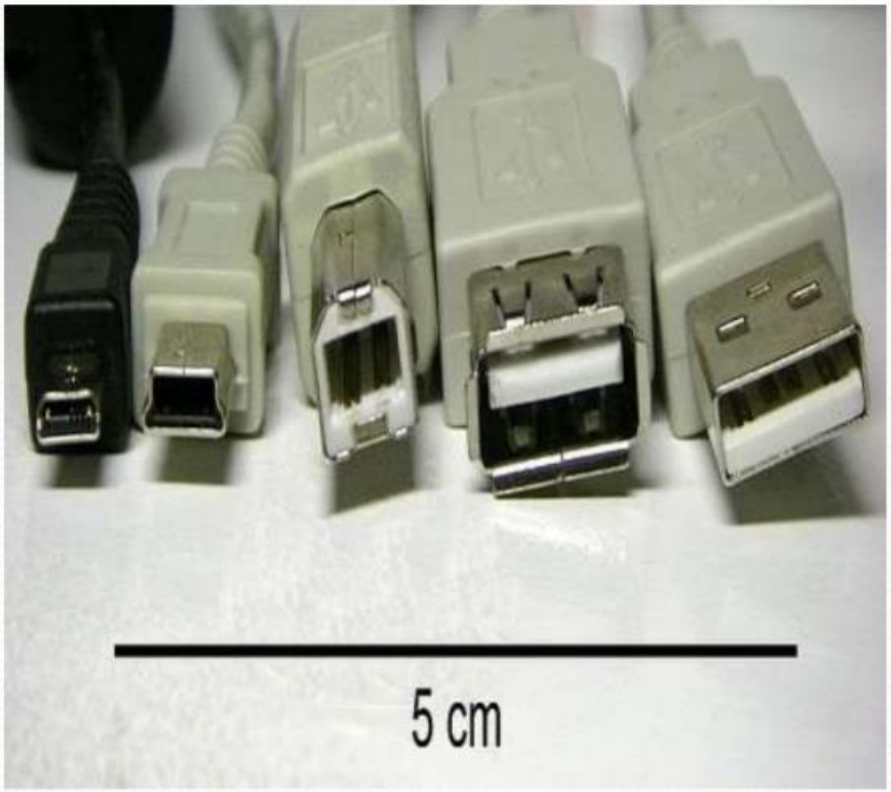
Key Features

- High performance
  - USB offers data transfer speeds at up to 4.8 Gbps
- Expandability
  - Up to 127 different peripheral devices may theoretically be connected to a single bus at one time
- Bus-supplied power
  - USB distributes the power to all connected devices, eliminating the need for an external power source for low power devices (flash drives, memory cards, Bluetooth)

Connector properties

- Availability
  - Consumer Products are expected to become available in 2010
- Usability
  - Most connectors cannot be plugged in upside down
- Durability
  - The standard connectors were designed to be robust
- Compatibility
  - Two-way communication is also possible. In USB 3.0, full-duplex communications are done when using SuperSpeed (USB 3.0) transfer

Connector Types



- male micro USB
- male mini USB B-type
- male B-type
- female A-type
- male A-type

Pin	Name	Cable Color	Description
1	VCC	Red	+5 V
2	D−	White	Data −
3	D+	Green	Data +
4	GND	Black	Ground

Maximum Useful Distance

- **USB 1.1** maximum cable length is 3 metres (9.8 ft)
- **USB 2.0** maximum cable length is 5 metres (16 ft)
- **USB 3.0** cable assembly may be of any length

USB 2.0 & USB 3.0

APPLICATIONS

- USB implements connections to storage devices using a set of standards called the USB mass storage device class.
- USB 3.0 can also support portable hard disk drives. The earlier versions of USBs were not supporting the 3.5 inch hard disk drives.
- These external drives usually contain a translating device that interfaces a drive of conventional technology (IDE, PATA, SATA, ATAPI, or even SCSI) to a USB port.

Linux USB drivers

Linux USB basics

Linux USB drivers

USB drivers (1)

USB core drivers

- Architecture independent kernel subsystem.
  Implements the USB bus specification.
  Outside the scope of this training.

USB host drivers

- Different drivers for each USB control hardware.
  Usually available in the Board Support Package.
  Architecture and platform dependent.
  Not covered yet by this training.

USB drivers (2)

USB device drivers

- Drivers for devices on the USB bus.
  The main focus of this course!
- Platform independent: when you use Linux on an embedded platform, you can use any USB device supported by Linux
  (cameras, keyboards, video capture, wi-fi dongles...).

USB device controller drivers

- For Linux systems with just a USB device controller (frequent in embedded systems).
  Not covered yet by this course.

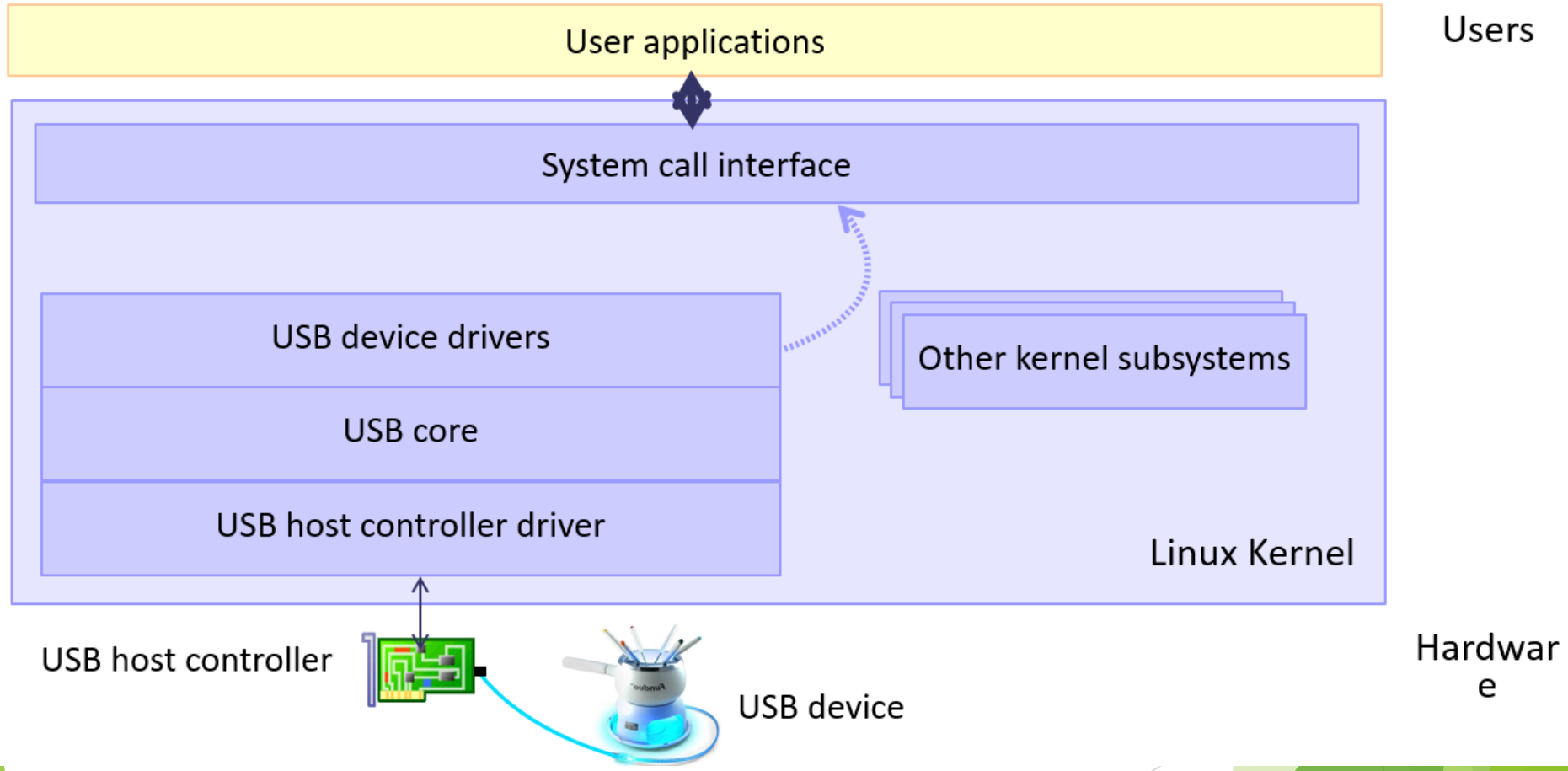
USB gadget drivers

Drivers for Linux systems with a USB device controller

- Typical example: digital cameras.
  You connect the device to a PC and see the camera as a USB storage device.
- USB device controller driver:
  Platform dependent. Supports the chip connecting to the USB bus.
- USB gadget drivers, platform independent. Examples:
  Ethernet gadget: implements networking through USB
  Storage gadget: makes the host see a USB storage device
  Serial gadget: for terminal-type of communication.

See Documentation/DocBook/gadget/ in kernel sources.

Linux USB support overview



USB host controllers - OHCI and UHCI

2 competing Host Control Device (HCD) interfaces

- OHCI - Open Host Controller Interface
  Compaq's implementation adopted as a standard for USB 1.0 and 1.1
  by the USB Implementers Forum (USB-IF).
  Also used for Firewire devices.
- UHCI - Universal Host Controller Interface.
  Created by Intel, insisting that other implementers use it and pay royalties for it. Only VIA licensed UHCI, and others stuck to OHCI.

This competition required to test devices for both host controller standards!

For USB 2.0, the USB-IF insisted on having only one standard.

USB host controllers - EHCI

EHCI - Extended Host Controller Interface.

- For USB 2.0. The only one to support high-speed transfers.
- Each EHCI controller contains four virtual HCD implementations to support Full Speed and Low Speed devices.
- On Intel and VIA chipsets, virtual HCDs are UHCI. Other chipset makers have OHCI virtual HCDs.

USB transfer speed

- Low-Speed: up to 1.5 Mbps
  Since USB 1.0
- Full-Speed: up to 12 Mbps
  Since USB 1.1
- Hi-Speed: up to 480 Mbps
  Since USB 2.0

Linux USB drivers

Linux USB basics

USB devices

USB descriptors

Operating system independent. Described in the USB specification

- Device - Represent the devices connected to the USB bus.
  Example: USB speaker with volume control buttons.
- Configurations - Represent the state of the device.
  Examples: Active, Standby, Initialization
- Interfaces - Logical devices.
  Examples: speaker, volume control buttons.
- Endpoints - Unidirectional communication pipes.
  Either `IN` (device to computer) or `OUT` (computer to device).

Control endpoints

- Used to configure the device, get information about it, send commands to it, retrieve status information.
- Simple, small data transfers.
- Every device has a control endpoint (endpoint 0), used to configure the device at insertion time.
- The USB protocol guarantees that the corresponding data transfers will always have enough (reserved) bandwidth.

Interrupt endpoints

- Transfer small amounts of data at a fixed rate each time the hosts asks the device for data.
- Guaranteed, reserved bandwidth.
- For devices requiring guaranteed response time, such as USB mice and keyboards.
- Note: different than hardware interrupts. Require constant polling from the host.

Bulk endpoints

- Large sporadic data transfers
  using all remaining available bandwidth.
- No guarantee on bandwidth or latency.
- Guarantee that no data is lost.
- Typically used for printers, storage or network devices.

Isochronous endpoints

- Also for large amounts of data.
- Guaranteed speed
  (often but not necessarily as fast as possible).
- No guarantee that all data makes it through.
- Used by real-time data transfers (typically audio and video).

The usb_endpoint_descriptor structure (1)

The usb_endpoint_descriptor structure contains all the USB-specific data announced by the device itself. Here are useful fields for driver writers:

- __u8 bEndpointAddress:
  USB address of the endpoint.
  It also includes the direction of the endpoint. You can use the USB_ENDPOINT_DIR_MASK bitmask to tell whether this is a USB_DIR_IN or USB_DIR_OUT endpoint.
  Example:

```
if ((endpoint->desc.bEndpointAddress &
 USB_ENDPOINT_DIR_MASK) == USB_DIR_IN)
```

The `usb_endpoint_descriptor` structure (2)

- `__u8 bmAttributes`:
  The type of the endpoint. You can use the `USB_ENDPOINT_XFERTYPE_MASK` bitmask to tell whether the type is `USB_ENDPOINT_XFER_ISOC`, `USB_ENDPOINT_XFER_BULK`, `USB_ENDPOINT_XFER_INT` or `USB_ENDPOINT_XFER_CONTROL`.
- `__u8 wMaxPacketSize`:
  Maximum size in bytes that the endpoint can handle. Note that if greater sizes are used, data will be split in `wMaxPacketSize` chunks.
- `__u8 bInterval`:
  For interrupt endpoints, device polling interval (in milliseconds).

Note that the above names do not follow Linux coding standards.
The Linux USB implementation kept the original name from the USB specification (http://www.usb.org/developers/docs/).

Interfaces

- Each interface encapsulates a single high-level function (USB logical connection). Example (USB webcam): video stream, audio stream, keyboard (control buttons).
- One driver is needed for each interface!
- Alternate settings: each USB interface may have different parameter settings. Example: different bandwidth settings for an audio interface. The initial state is in the first setting, (number 0).
- Alternate settings are often used to control the use of periodic endpoints, such as by having different endpoints use different amounts of reserved USB bandwidth. All standards-compliant USB devices that use isochronous endpoints will use them in non-default settings.

The `usb_interface` structure (1)

USB interfaces are represented by the `usb_interface` structure. It is what the USB core passes to USB drivers.

- `struct usb_host_interface *altsetting;`
  List of alternate settings that may be selected for this interface, in no particular order.
  The `usb_host_interface` structure for each alternate setting allows to access the `usb_endpoint_descriptor` structure for each of its endpoints:
  `interface->alsetting[i]->endpoint[j]->desc`
- `unsigned int num_altsetting;`
  The number of alternate settings.

The `usb_interface` structure (2)

- `struct usb_host_interface *cur_altsetting;`
  The currently active alternate setting.
- `int minor;`
  Minor number this interface is bound to.
  (for drivers using `usb_register_dev()`, described later).

Other fields in the structure shouldn't be needed by USB drivers.

Configurations

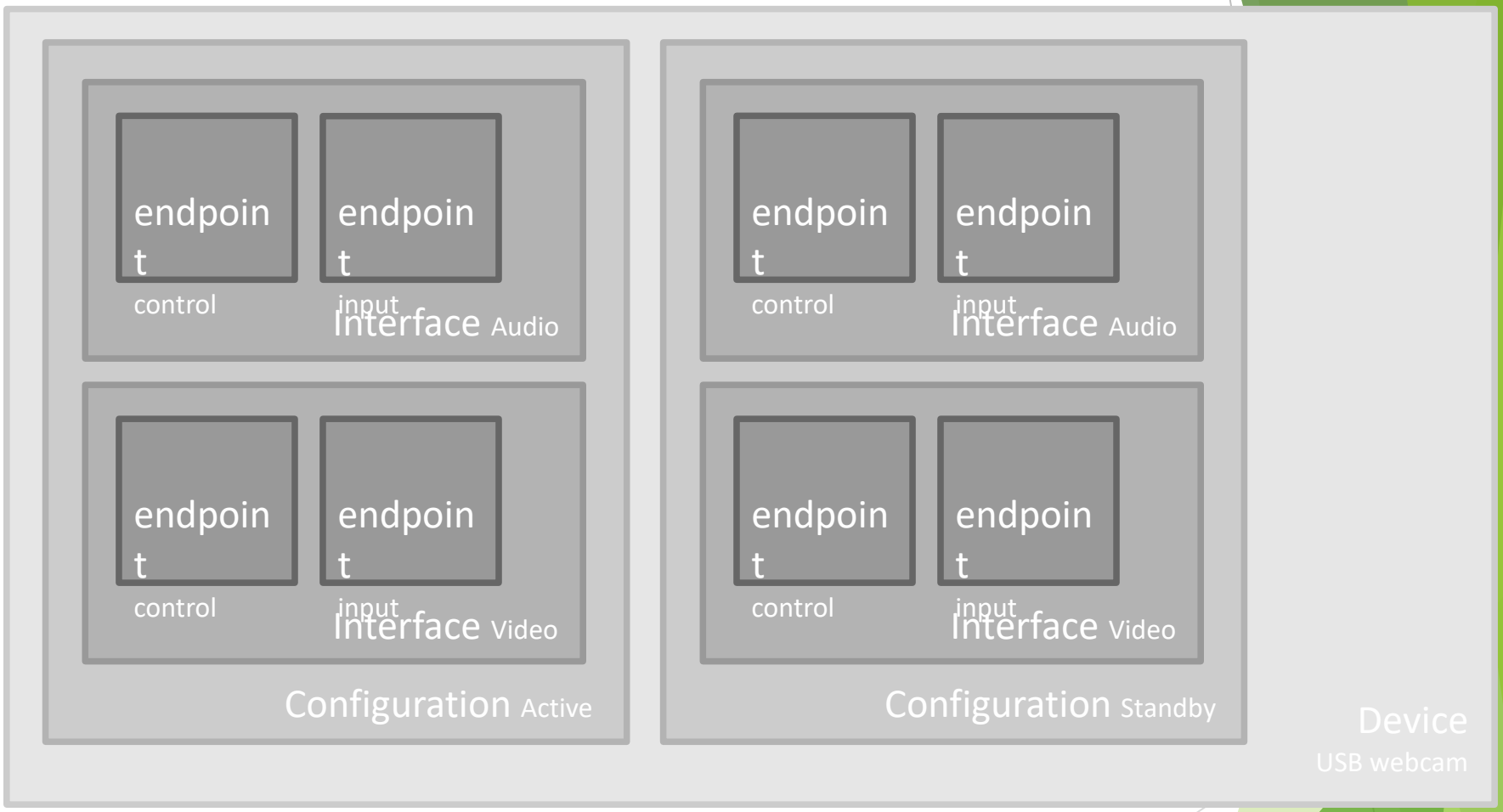
Interfaces are bundled into configurations.

- Configurations represent the state of the device.
  Examples: Active, Standby, Initialization
- Configurations are described
  with the `usb_host_config` structure.
- However, drivers do not need to access this structure.

Devices

- Devices are represented by the `usb_device` structure.
- We will see later that several USB API functions need such a structure.
- Many drivers use the `interface_to_usbdev()` function to access their `usb_device` structure from the `usb_interface` structure they are given by the USB core.

USB device overview



USB devices - Summary

- Hierarchy: device → configurations → interfaces → endpoints
- 4 different types of endpoints
  - control: device control, accessing information, small transfers. Guaranteed bandwidth.
  - interrupt (keyboards, mice...): data transfer at a fixed rate. Guaranteed bandwidth.
  - bulk (storage, network, printers...): use all remaining bandwidth. No bandwidth or latency guarantee.
  - isochronous (audio, video...): guaranteed speed. Possible data loss.

Linux USB drivers

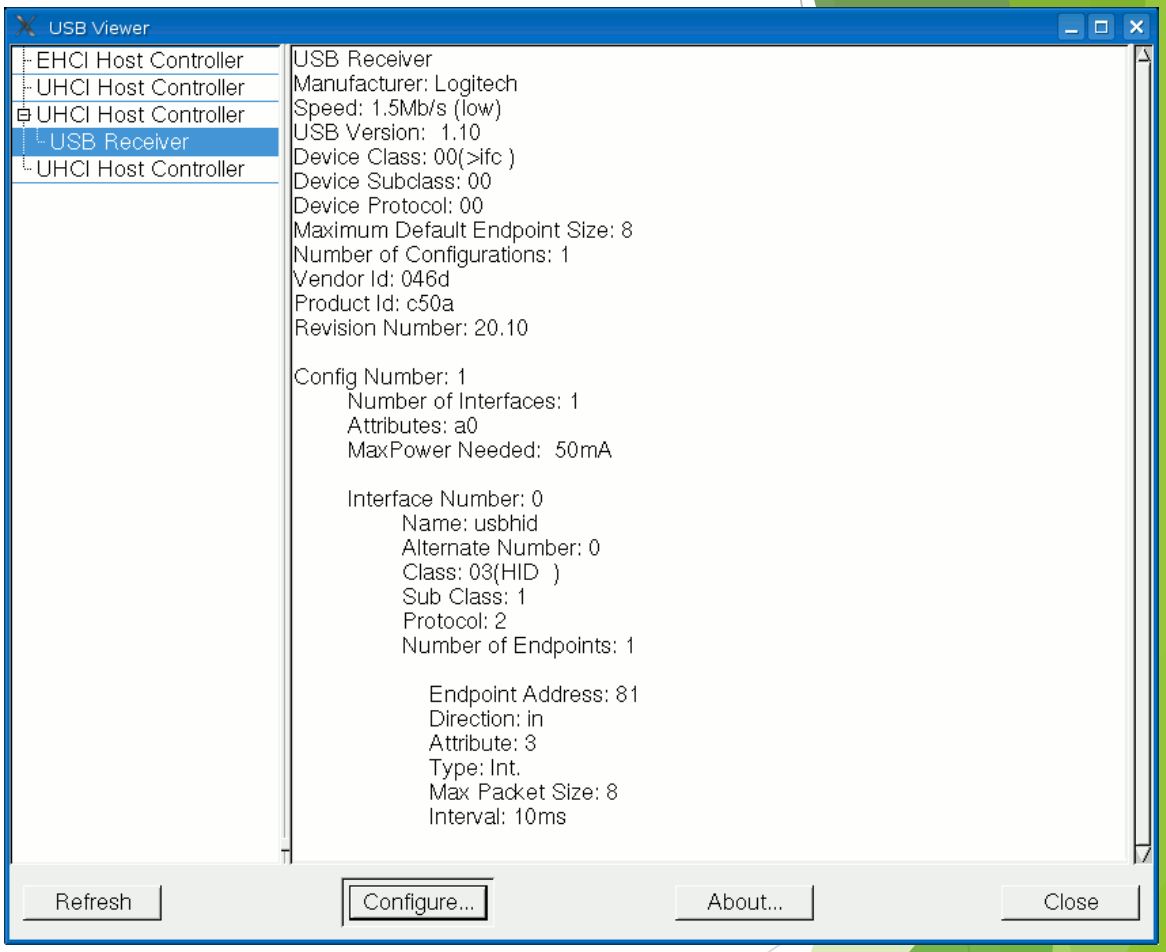
Linux USB basics

User-space representation

usbview

http://usbview.sourceforge.net

Graphical display of the contents of `/proc/bus/usb/devices`.



usbtree

http://www.linux-usb.org/usbtree

Also displays information from `/proc/bus/usb/devices`:

```
> usbtree
 \/:  Bus 04.Port 1: Dev 1, Class=root_hub, Driver=ehci_hcd/6p,
 480M
 /:  Bus 03.Port 1: Dev 1, Class=root_hub, Driver=uhci_hcd/2p, 12M
 /:  Bus 02.Port 1: Dev 1, Class=root_hub, Driver=uhci_hcd/2p, 12M
     |__ Port 1: Dev 7, If 0, Class=HID, Driver=usbhid, 1.5M
 /:  Bus 01.Port 1: Dev 1, Class=root_hub, Driver=uhci_hcd/2p, 12M
```

Linux USB drivers

Linux USB communication

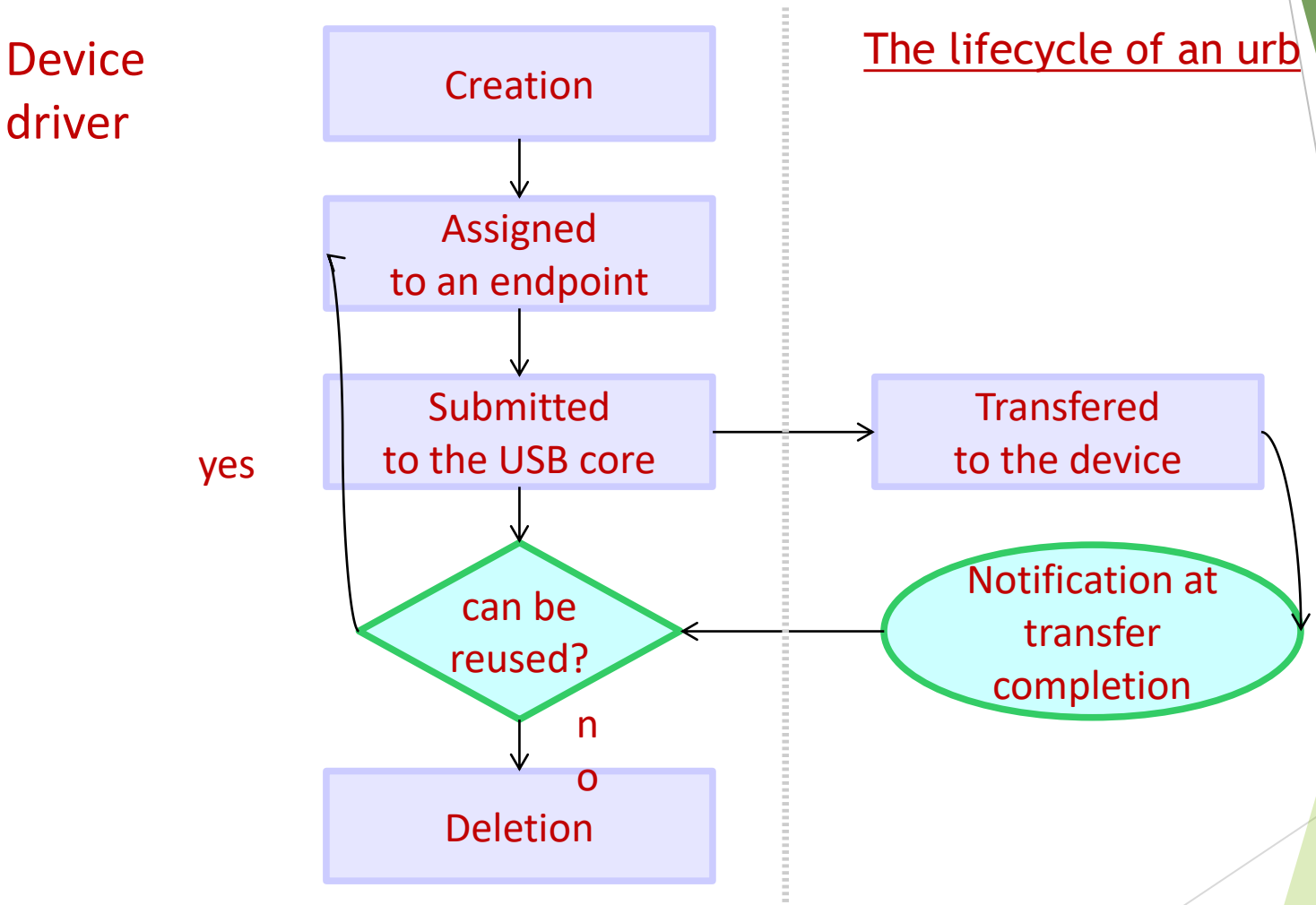
USB Request Blocks

USB Request Blocks

- Any communication between the host and device is done asynchronously using USB Request Blocks (urbs).
- They are similar to packets in network communications.
- Every endpoint can handle a queue of urbs.
- Every urb has a completion handler.
- A driver may allocate many urbs for a single endpoint, or reuse the same urb for different endpoints.

See `Documentation/usb/URB.txt` in kernel sources.

Urban life


Device driver
The lifecycle of an urb
USB core (controller driver)
Creation
Assigned to an endpoint
Submitted to the USB core
Transfered to the device
yes
can be reused?
Notification at transfer completion
no
Deletion

The `urb` structure (1)

Fields of the `urb` structure useful to USB device drivers:

- `struct usb_device *dev;`
  Device the urb is sent to.
- `unsigned int pipe;`
  Information about the endpoint in the target device.
- `int status;`
  Transfer status.
- `unsigned int transfer_flags;`
  Instructions for handling the urb.

The `urb` structure (2)

- `void * transfer_buffer;`
  Buffer storing transferred data.
  Must be created with `kmalloc()`!
- `dma_addr_t transfer_dma;`
  Data transfer buffer when DMA is used.
- `int transfer_buffer_length;`
  Transfer buffer length.
- `int actual_length;`
  Actual length of data received or sent by the urb.
- `usb_complete_t complete;`
  Completion handler called when the transfer is complete.

The `urb` structure (3)

- `void *context;`
  Data blob which can be used in the completion handler.
- `unsigned char *setup_packet;` (control urbs)
  Setup packet transferred before the data in the transfer buffer.
- `dma_addr_t setup_dma;` (control urbs)
  Same, but when the setup packet is transferred with DMA.
- `int interval;` (isochronous and interrupt urbs)
  Urb polling interval.
- `int error_count;` (isochronous urbs)
  Number of isochronous transfers which reported an error.

The `urb` structure (4)

- `int start_frame;` (isochronous urbs)
  Sets or returns the initial frame number to use.
- `int number_of_packets;` (isochronous urbs)
  Number of isochronous transfer buffers to use.
- `struct usb_iso_packet_descriptor` (isochronous urbs)
  `iso_frame_desc[0];`
  Allows a single urb to define multiple isochronous transfers at once.

Creating pipes

Functions used to initialize the `pipe` field of the `urb` structure:

- Control pipes
  `usb_sndctrlpipe()`, `usb_rcvctrlpipe()`
- Bulk pipes
  `usb_sndbulkpipe()`, `usb_rcvbulkpipe()`
- Interrupt pipes
  `usb_sndintpipe()`, `usb_rcvintpipe()`
- Isochronous pipes
  `usb_sndisocpipe()`, `usb_rcvisocpipe()`

send (out)

receive (in)

Prototype

```
unsigned int usb_[snd/rcv][ctrl/bulk/int/isoc]pipe(
   struct usb_device *dev, unsigned int endpoint);
```

Creating urbs

- `urb` structures must always be allocated with the `usb_alloc_urb()` function.
  That's needed for reference counting used by the USB core.

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

struct urb *usb_alloc_urb(
   int iso_packets,      // Number of isochronous
                         // packets the urb should contain.
                         // 0 for other transfer types
   gfp_t mem_flags);     // Standard kmalloc() flags
```

- Check that it didn't return `NULL` (allocation failed)!
- Typical example:
  `urb = usb_alloc_urb(0, GFP_KERNEL);`

Freeing urbs

- Similarly, you have to use a dedicated function to release urbs:

```
void usb_free_urb(struct urb *urb);
```

USB Request Blocks - Summary

- Basic data structure used in any USB communication.
- Implemented by the `struct urb` type.
- Must be created with the `usb_alloc_urb()` function. Shouldn't be allocated statically or with `kmalloc()`.
- Must be deleted with `usb_free_urb()`.

Linux USB drivers

Linux USB communication

Initializing and submitting urbs

Initializing interrupt urbs

```
void usb_fill_int_urb (
   struct urb *urb,                  // urb to be initialized
   struct usb_device *dev,           // device to send the urb to
   unsigned int pipe,                // pipe (endpoint and device
   specific)
   void *transfer_buffer,            // transfer buffer
   int buffer_length,                // transfer buffer size
   usb_complete_t complete,          // completion handler
   void *context,                    // context (for handler)
   int interval                      // Scheduling interval (see next
   page)
   );
```

- This doesn't prevent you from making more changes to the urb fields before urb submission.
- The `transfer_flags` field needs to be set by the driver.

urb scheduling interval

For interrupt and isochronous transfers

- Low-Speed and Full-Speed devices:
  the `interval` unit is frames (ms)
- Hi-Speed devices:
  the `interval` unit is microframes (1/8 ms)

Initializing bulk urbs

Same parameters as in `usb_fill_int_urb()`, except that there is no `interval` parameter.

```
void usb_fill_bulk_urb (
  struct urb *urb,                  // urb to be initialized
  struct usb_device *dev,           // device to send the urb to
  unsigned int pipe,                // pipe (endpoint and device
  specific)
  void *transfer_buffer,            // transfer buffer
  int buffer_length,                // transfer buffer size
  usb_complete_t complete,          // completion handler
  void *context,                    // context (for handler)
  );
```

Initializing control urbs

Same parameters as in `usb_fill_bulk_urb()`, except that there is a `setup_packet` parameter.

```
void usb_fill_control_urb (
   struct urb *urb,                  // urb to be initialized
   struct usb_device *dev, // device to send the urb to
   unsigned int pipe,                // pipe (endpoint and device
   specific)
   unsigned char *setup_packet, // setup packet data
   void *transfer_buffer,  // transfer buffer
   int buffer_length,                // transfer buffer size
   usb_complete_t complete,    // completion handler
   void *context,                    // context (for handler)
   );
```

Note that many drivers use the `usb_control_msg()` function instead (explained later).

Initializing isochronous urbs

No helper function. Has to be done manually by the driver.

```
for (i=0; i < USBVIDEO_NUMSBUF; i++) {
    int j, k;
    struct urb *urb = uvd->sbuf[i].urb;
    urb->dev = dev;
    urb->context = uvd;
    urb->pipe = usb_rcvisocpipe(dev, uvd->video_endp);
    urb->interval = 1;
    urb->transfer_flags = URB_ISO_ASAP;
    urb->transfer_buffer = uvd->sbuf[i].data;
    urb->complete = usbvideo_IsocIrq;
    urb->number_of_packets = FRAMES_PER_DESC;
    urb->transfer_buffer_length = uvd->iso_packet_len * FRAMES_PER_DESC;
    for (j=k=0; j < FRAMES_PER_DESC; j++, k += uvd->iso_packet_len) {
        urb->iso_frame_desc[j].offset = k;
        urb->iso_frame_desc[j].length = uvd->iso_packet_len;
    }
}
```

drivers/media/video/usbvideo/usbvideo.c

Allocating DMA buffers (1)

You can use the usb_buffer_alloc() function to allocate a DMA consistent buffer:

```
void *usb_buffer_alloc (
    struct usb_device *dev, // device
    size_t size,            // buffer size
    gfp_t mem_flags,        // kmalloc() flags
    dma_addr_t *dma         // (output) DMA address
);                              // of the buffer.
```

Example:

```
buf = usb_buffer_alloc(dev->udev,
    count, GFP_KERNEL, &urb->transfer_dma);
```

Allocating DMA buffers (2)

- To use these buffers, use the `URB_NO_TRANSFER_DMA_MAP` or `URB_NO_SETUP_DMA_MAP` settings for `urb->transfer_flags` to indicate that `urb->transfer_dma` or `urb->setup_dma` are valid on submit.
- Examples:

```
urb->transfer_flags |= URB_NO_TRANSFER_DMA_MAP;
u->transfer_flags |= URB_NO_SETUP_DMA_MAP;
```

- Freeing these buffers:

```
void usb_buffer_free (
 struct usb_device *dev,     // device
 size_t size,                    // buffer size
 void *addr,                     // CPU address of buffer
 dma_addr_t dma                  // DMA address of buffer
);
```

Submitting urbs

After creating and initializing the urb

```
int usb_submit_urb(
   struct urb *urb,          // urb to submit
   int mem_flags);     // kmalloc() flags
```

`mem_flags` is used for internal allocations performed by `usb_submit_urb()`. Settings that should be used:

- `GFP_ATOMIC`: called from code which cannot sleep: a urb completion handler, hard or soft interrupts. Or called when the caller holds a spinlock.
- `GPF_NOIO`: in some cases when block storage is used.
- `GFP_KERNEL`: in other cases.

usb_submit_urb return values

`usb_submit_urb()` immediately returns:

- `0`: Request queued
- `-ENOMEM`: Out of memory
- `-ENODEV`: Unplugged device
- `-EPIPE`: Stalled endpoint
- `-EAGAIN`: Too many queued ISO transfers
- `-EFBIG`: Too many requested ISO frames
- `-EINVAL`: Invalid INT interval
  More than one packet for INT

Canceling urbs asynchronously

To cancel a submitted urb without waiting

- `int usb_unlink_urb(struct urb *urb);`
- Success: returns `-EINPROGRESS`
- Failure: any other return value. It can happen:
  - When the urb was never submitted
  - When the has already been unlinked
  - When the hardware is done with the urb, even if the completion handler hasn't been called yet.
- The corresponding completion handlers will still be run and will see `urb->status == -ECONNRESET`.

Canceling urbs synchronously

To cancel an urb and wait for all completion handlers to complete

- This guarantees that the urb is totally idle and can be reused.
- `void usb_kill_urb(struct urb *urb);`
- Typically used in a `disconnect()` callback or `close()` function.
- Caution: this routine mustn't be called in situations which can not sleep: in interrupt context, in a completion handler, or when holding a spinlock.

See comments in `drivers/usb/core/urb.c` in kernel sources for useful details.

Initializing and submitting urbs - Summary

- `urb` structure fields can be initialized with helper functions `usb_fill_int_urb()`, `usb_fill_bulk_urb()`, `usb_fill_control_urb()`
- Isochronous urbs have to be initialized by hand.
- The `transfer_flags` field must be initialized manually by each driver.
- Use the `usb_submit_urb()` function to queue urbs.
- Submitted urbs can be canceled using `usb_unlink_urb()` (asynchronous) or `usb_kill_urb()` (synchronous).

Linux USB drivers

Linux USB communication

Completion handlers

When is the completion handler called?

The completion handler is called in interrupt context, in only 3 situations.
Check the error value in `urb->status`.

- After the data transfer successfully completed.
  `urb->status == 0`
- Error(s) happened during the transfer.
- The urb was unlinked by the USB core.

`urb->status` should only be checked from the completion handler!

Transfer status (1)

Described in Documentation/usb/error-codes.txt

The urb is no longer “linked” in the system

- -ECONNRESET
  The urb was unlinked by usb_unlink_urb().
- -ENOENT
  The urb was stopped by usb_kill_urb().
- -ESHUTDOWN
  Error in from the host controller driver. The device was disconnected from the system, the controller was disabled, or the configuration was changed while the urb was sent.
- -ENODEV
  Device removed. Often preceded by a burst of other errors, since the hub driver doesn't detect device removal events immediately.

Transfer status (2)

Typical hardware problems with the cable or the device (including its firmware)

- -EPROTO
  Bitstuff error, no response packet received in time by the hardware,
  or unknown USB error.
- -EILSEQ
  CRC error, no response packet received in time, or unknown USB error.
- -EOVERFLOW
  The amount of data returned by the endpoint was greater than either the max packet size of the endpoint or the remaining buffer size. "Babble".

Transfer status (3)

Other error status values

- -EINPROGRESS
  Urb not completed yet. Your driver should never get this value.
- -ETIMEDOUT
  Usually reported by synchronous USB message functions when the specified timeout was exceed.
- -EPIPE
  Endpoint stalled. For non-control endpoints, reset this status with `usb clear halt()`.
- -ECOMM
  During an IN transfer, the host controller received data from an endpoint faster than it could be written to system memory.

Transfer status (4)

- -ENOSR
  During an OUT transfer, the host controller could not retrieve data from system memory fast enough to keep up with the USB data rate.
- -EREMOTEIO
  The data read from the endpoint did not fill the specified buffer, and URB_SHORT_NOT_OK was set in `urb->transfer_flags`.
- -EXDEV
  Isochronous transfer only partially completed.
  Look at individual frame status for details.
- -EINVAL
  Typically happens with an incorrect urb structure field or `usb_submit_urb()` function parameter.

Completion handler implementation

- Prototype:

```
void (*usb_complete_t)(
 struct urb *,     // The completed urb
 struct pt_regs *     // Register values at the time
                      // of the corresponding interrupt (if
any)
);
```

- Remember you are in interrupt context:
  - Do not execute call which may sleep (use GFP_ATOMIC, etc.).
  - Complete as quickly as possible.
    Schedule remaining work in a tasklet if needed.

Completion handler - Summary

- The completion handler is called in interrupt context. Don't run any code which could sleep!
- Check the `urb->status` value in this handler, and not before.
- Success: `urb->status == 0`
- Otherwise, error status described in `Documentation/usb/error-codes.txt`.

Linux USB drivers

Writing USB drivers

Supported devices

What devices does the driver support?

Or what driver supports a given device?

- Information needed by user-space, to find the right driver to load or remove after a USB hotplug event.
- Information needed by the driver, to call the right `probe()` and `disconnect()` driver functions (see later).

Such information is declared in a `usb_device_id` structure by the driver `init()` function.

The `usb_device_id` structure (1)

Defined according to USB specifications and described in `include/linux/mod_devicetable.h`.

- `__u16 match_flags`
  Bitmask defining which fields in the structure are to be matched against. Usually set with helper functions described later.
- `__u16 idVendor, idProduct`
  USB vendor and product id, assigned by the USB-IF.
- `__u16 bcdDevice_lo, bcdDevice_hi`
  Product version range supported by the driver, expressed in binary-coded decimal (BCD) form.

The `usb_device_id` structure (2)

- `__u8 bDeviceClass, bDeviceSubClass, bDeviceProtocol`
  Class, subclass and protocol of the device.
  Numbers assigned by the USB-IF.
  Products may choose to implement classes, or be vendor-specific.
  Device classes specify the behavior of all the interfaces on a device.
- `__u8 bInterfaceClass, bInterfaceSubclass, bInterfaceProtocol`
  Class, subclass and protocol of the individual interface.
  Numbers assigned by the USB-IF.
  Interface classes only specify the behavior of a given interface.
  Other interfaces may support other classes.
- `kernel_ulong_t driver_info`

The `usb_device_id` structure (3)

- `kernel_ulong_t driver_info`

  Holds information used by the driver. Usually it holds a pointer to a descriptor understood by the driver, or perhaps device flags.

  This field is useful to differentiate different devices from each other in the `probe()` function.

Declaring supported devices (1)

`USB_DEVICE(vendor, product)`

- Creates a `usb_device_id` structure which can be used to match only the specified vendor and product ids.
- Used by most drivers for non-standard devices.

`USB_DEVICE_VER(vendor, product, lo, hi)`

- Similar, but only for a given version range.
- Only used 11 times throughout Linux 2.6.18!

Declaring supported devices (2)

`USB_DEVICE_INFO (class, subclass, protocol)`

- Matches a specific class of USB devices.

`USB_INTERFACE_INFO (class, subclass, protocol)`

- Matches a specific class of USB interfaces.

The above 2 macros are only used in the implementations of standard device and interface classes.

Declaring supported devices (3)

Created `usb_device_id` structures are declared with the `MODULE_DEVICE_TABLE()` macro as in the below example:

```
/* Example from drivers/usb/net/catc.c */
static struct usb_device_id catc_id_table [] = {
    { USB_DEVICE(0x0423, 0xa) }, /* CATC Netmate, Belkin F5U011 */
    { USB_DEVICE(0x0423, 0xc) }, /* CATC Netmate II, Belkin F5U111
*/
    { USB_DEVICE(0x08d1, 0x1) }, /* smartBridges smartNIC */
    { }                          /* Terminating entry */
};

MODULE_DEVICE_TABLE(usb, catc_id_table);
```

Note that `MODULE_DEVICE_TABLE()` is also used with other subsystems: `pci`, `pcmcia`, `serio`, `isapnp`, `input`...

Supported devices - Summary

- Drivers need to announce the devices they support in `usb_device_id` structures.
- Needed for user space to know which module to (un)load, and for the kernel which driver code to execute, when a device is inserted or removed.
- Most drivers use `USB_DEVICE()` to create the structures.
- These structures are then registered with `MODULE_DEVICE_TABLE(usb, xxx)`.

Linux USB drivers

Writing USB drivers

Registering a USB driver

The `usb_driver` structure

USB drivers must define a `usb_driver` structure:

- `const char *name`
  Unique driver name. Usually be set to the module name.
- `const struct usb_device_id *id_table;`
  The table already declared with `MODULE_DEVICE_TABLE()`.
- `int (*probe) (struct usb_interface *intf, const struct usb_device_id *id);`
  Probe callback (detailed later).
- `void (*disconnect) (struct usb_interface *intf);`
  Disconnect callback (detailed later).

Optional `usb_driver` structure fields

- ```
  int (*suspend) (struct usb_interface *intf,
                  pm_message_t message);
  int (*resume) (struct usb_interface *intf);
  ```
  Power management: callbacks called before and after the USB core suspends and resumes the device.
- ```
  void (*pre_reset) (struct usb_interface *intf);
  void (*post_reset) (struct usb_interface
  *intf);
  ```
  Called by `usb_reset_composite_device()` before and after it performs a USB port reset.

Driver registration

Use usb_register() to register your driver. Example:

```
/* Example from drivers/usb/input/mtouchusb.c */
static struct usb_driver mtouchusb_driver = {
        .name           = "mtouchusb",
        .probe          = mtouchusb_probe,
        .disconnect     = mtouchusb_disconnect,
        .id_table       = mtouchusb_devices,
};

static int __init mtouchusb_init(void)
{
        dbg("%s - called", __FUNCTION__);
        return usb_register(&mtouchusb_driver);
}
```

Driver unregistration

Use usb_deregister() to register your driver. Example:

```
/* Example from drivers/usb/input/mtouchusb.c */
static void __exit mtouchusb_cleanup(void)
{
        dbg("%s - called", __FUNCTION__);
        usb_deregister(&mtouchusb_driver);
 }
```

probe() and disconnect() functions

- The `probe()` function is called by the USB core to see if the driver is willing to manage a particular interface on a device.
- The driver should then make checks on the information passed to it about the device.
- If it decides to manage the interface, the `probe()` function will return `0`. Otherwise, it will return a negative value.
- The `disconnect()` function is called by the USB core when a driver should no longer control the device (even if the driver is still loaded), and should do some clean-up.

Context: USB hub kernel thread

- The `probe()` and `disconnect()` callbacks are called in the context of the USB hub kernel thread.
- So, it is legal to call functions which may sleep in these functions.
- However, all addition and removal of devices is managed by this single thread.
- Most of the probe function work should indeed be done when the device is actually opened by a user. This way, this doesn't impact the performance of the kernel thread in managing other devices.

probe() function work

- In this function the driver should initialize local structures which it may need to manage the device.
- In particular, it can take advantage of information it is given about the device.
- For example, drivers usually need to detect endpoint addresses and buffer sizes.

Time to show and explain examples in detail!

usb_set_intfdata() / usb_get_intfdata()

```
static inline void usb_set_intfdata (
    struct usb_interface *intf,
    void *data);
```

- Function used in `probe()` functions to attach collected device data to an interface. Any pointer will do!
- Useful to store information for each device supported by a driver, without having to keep a static data array.
- The `usb_get_intfdata()` function is typically used in the device open functions to retrieve the data.
- Stored data need to be freed in `disconnect()` functions: `usb_set_intfdata(interface, NULL);`

Plenty of examples are available in the kernel sources.

Linux USB drivers

Writing USB drivers

USB transfers without URBs

Transfers without URBs

The kernel provides two `usb_bulk_msg()` and `usb_control_msg()` helper functions that make it possible to transfer simple bulk and control messages, without having to:

- Create or reuse an urb structure,
- Initialize it,
- Submit it,
- And wait for its completion handler.

Transfers without URBs - constraints

- These functions are synchronous and will make your code sleep. You must not call them from interrupt context or with a spinlock held.
- You cannot cancel your requests, as you have no handle on the URB used internally. Make sure your `disconnect()` function can wait for these functions to complete.

See the kernel sources for examples using these functions!

USB device drivers - Summary

Module loading

- Declare supported devices (interfaces).
- Bind them to `probe()` and `disconnect()` functions.

Supported devices are found

- probe() functions for matching interface drivers are called.
- They record interface information and register resources or services.

Devices are opened

- This calls data access functions registered by the driver.
- URBs are initialized.
- Once the transfers are over, completion functions are called. Data are copied from/to user-space.

Devices are removed

- The `disconnect()` functions are called.
- The drivers may be unloaded.

Advice for embedded system developers

If you need to develop a USB device driver for an embedded Linux system.

- Develop your driver on your GNU/Linux development host!
- The driver will run with no change on the target Linux system (provided you wrote portable code!): all USB device drivers are platform independent.
- Your driver will be much easier to develop on the host, because of its flexibility and the availability of debugging and development tools.

PCI Driver

Some background on PCI

ISA: Industry Standard Architecture (1981)

PCI: Peripheral Component Interconnect

An Intel-backed industry initiative (1992-9)

Main goals:

- Improve data-xfers to/from peripheral devices
- Eliminate (or reduce) platform dependencies
- Simplify adding/removing peripheral devices
- Lower total consumption of electrical power

Some background on PCI

The PCI architecture was designed as a replacement for the ISA standard, with three main goals:

- to get better performance when transferring data between the computer and its peripherals
- to be as platform independent as possible
- and to simplify adding and removing peripherals to the system.

Some background on PCI

The PCI bus achieves better performance by using a higher clock rate than ISA; its clock runs at 25 or 33 MHz (its actual rate being a factor of the system clock), and 66-MHz and even 133-MHz implementations have recently been deployed as well.

It is equipped with a 32-bit data bus, and a 64-bit extension has been included in the specification.

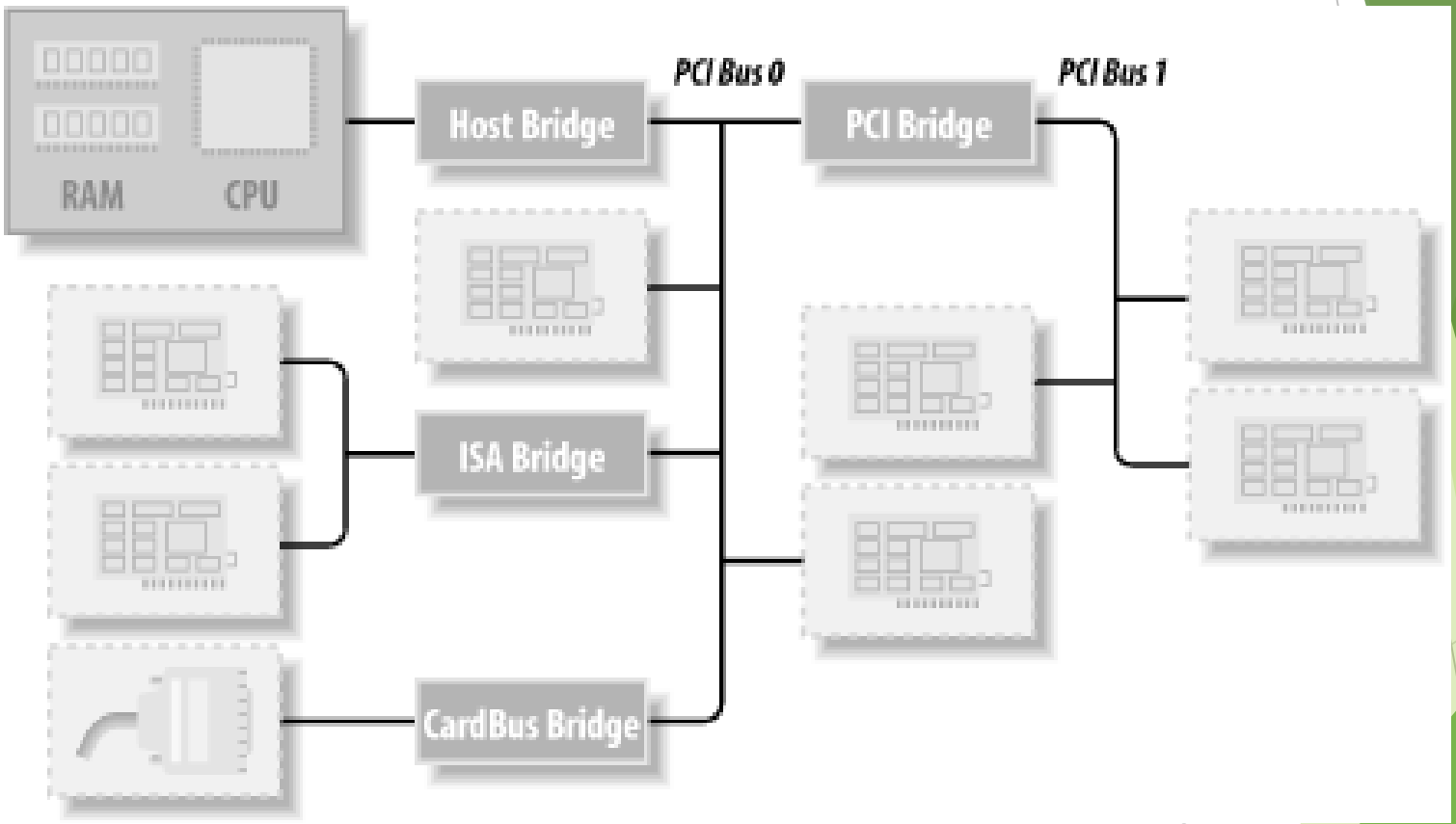
The device driver must be able to access configuration information in the device in order to complete initialization. This happens without the need to perform any probing.

PCI Addressing

Each PCI peripheral is identified by a bus number, a device number, and a function number. The PCI specification permits a single system to host up to 256 buses, but because 256 buses are not sufficient for many large systems, Linux now supports PCI domains. Each PCI domain can host up to 256 buses. Each bus hosts up to 32 devices, and each device can be a multifunction board (such as an audio device with an accompanying CD-ROM drive) with a maximum of eight functions.

When the hardware address is displayed, it can be shown as two values (an 8-bit bus number and an 8-bit device and function number), as three values (bus, device, and function), or as four values (domain, bus, device, and function); all the values are usually displayed in hexadecimal.

PCI Addressing



The ‘lspci’ command

Linux scans PCI Configuration Space

It builds a list of ‘pci_dev_struct’ objects

It exports partial info using a ‘/proc’ file

You can view this info using a command: $
/sbin/lspci

Or you can directly view the /proc/pci file:

$ cat /proc/pci

1. Default Usage

By default it will display all the device information as shown below. The first field is the slot information in this format: [domain:]bus:device.function

In this example, since all the domain are 0, lspci will not display the domain.

```
# lspci

00:00.0 Host bridge: Intel Corporation 5500 I/O Hub to ESI Port (rev 13)

00:01.0 PCI bridge: Intel Corporation 5520/5500/X58 I/O Hub PCI Express Root Port 1 (rev 13)

00:09.0 PCI bridge: Intel Corporation 7500/5520/5500/X58 I/O Hub PCI Express Root Port 9 (rev 13)

00:14.0 PIC: Intel Corporation 7500/5520/5500/X58 I/O Hub System Management Registers (rev 13)

00:14.1 PIC: Intel Corporation 7500/5520/5500/X58 I/O Hub GPIO and Scratch Pad Registers (rev 13)

00:14.2 PIC: Intel Corporation 7500/5520/5500/X58 I/O Hub Control Status and RAS Registers (rev 13)

00:1a.0 USB controller: Intel Corporation 82801I (ICH9 Family) USB UHCI Controller #4 (rev 02)

00:1c.0 PCI bridge: Intel Corporation 82801I (ICH9 Family) PCI Express Port 1 (rev 02)

00:1d.0 USB controller: Intel Corporation 82801I (ICH9 Family) USB UHCI Controller #1 (rev 02)

00:1e.0 PCI bridge: Intel Corporation 82801 PCI Bridge (rev 92)

00:1f.0 ISA bridge: Intel Corporation 82801IB (ICH9) LPC Interface Controller (rev 02)

00:1f.2 IDE interface: Intel Corporation 82801IB (ICH9) 2 port SATA Controller [IDE mode] (rev 02)

01:00.0 Ethernet controller: Broadcom Corporation NetXtreme II BCM5709 Gigabit Ethernet (rev 20)

01:00.1 Ethernet controller: Broadcom Corporation NetXtreme II BCM5709 Gigabit Ethernet (rev 20)

03:00.0 RAID bus controller: LSI Logic / Symbios Logic MegaRAID SAS 2108 [Liberator] (rev 05)

06:03.0 VGA compatible controller: Matrox Electronics Systems Ltd. MGA G200eW WPCM450 (rev 0a)
```

Dump PCI Info in Different Format

If you want to pass the output of the lspci command to a shell script, you may want to use -m option (or -mm option) as shown below.

This option is also helpful when you want to view the subsystem information. For example, for the RAID controller, the default output just says that is is using LSI Logic RAID controller. But, the following output displays the subsystem, which is DELL PERC H700 Integrated RAID controller system.

```
# lspci -m

00:00.0 "Host bridge" "Intel Corporation" "5500 I/O Hub to ESI Port" -r13 "Dell"
"PowerEdge R610 I/O Hub to ESI Port"

00:09.0 "PCI bridge" "Intel Corporation" "7500/5520/5500/X58 I/O Hub PCI Express Root
Port 9" -r13 "" ""

00:14.0 "PIC" "Intel Corporation" "7500/5520/5500/X58 I/O Hub System Management
Registers" -r13 "" ""

00:1a.0 "USB controller" "Intel Corporation" "82801I (ICH9 Family) USB UHCI
Controller #4" -r02 "Dell" "PowerEdge R610 USB UHCI Controller"

00:1f.0 "ISA bridge" "Intel Corporation" "82801IB (ICH9) LPC Interface Controller" -
r02 "Dell" "PowerEdge R610 82801IB (ICH9) LPC Interface Controller"

00:1f.2 "IDE interface" "Intel Corporation" "82801IB (ICH9) 2 port SATA Controller
[IDE mode]" -r02 -p8f "Dell" "PowerEdge R610 SATA IDE Controller"

01:00.0 "Ethernet controller" "Broadcom Corporation" "NetXtreme II BCM5709 Gigabit
Ethernet" -r20 "Dell" "PowerEdge R610 BCM5709 Gigabit Ethernet"

03:00.0 "RAID bus controller" "LSI Logic / Symbios Logic" "MegaRAID SAS 2108
[Liberator]" -r05 "Dell" "PERC H700 Integrated"

06:03.0 "VGA compatible controller" "Matrox Electronics Systems Ltd." "MGA G200eW
WPCM450" -r0a "Dell" "PowerEdge R610 MGA G200eW WPCM450"
```

Output in Tree Format

The -t option will display the output in tree format with information about bus, and how devices are connected to those buses as shown below. The output will be only using the numerical ids.

```
# lspci -t

-[0000:00]-+-00.0

           +-01.0-[01]--+-00.0

           |            \-00.1

           +-03.0-[02]--+-00.0

           |            \-00.1

           +-07.0-[04]--

           +-09.0-[05]--

           +-14.0

           +-14.1

           +-1c.0-[03]----00.0

           +-1d.0

           +-1e.0-[06]----03.0

           +-1f.0
```

Detailed Device Information

If you want to look into details of a particular device, use -v to get more information. This will display information about all the devices. The output of this command will be very long, and you need to scroll down and view the appropriate section.

For additional level for verbosity, you can use -vv or -vvv.

In the following example, I've given output of only the RAID controller device.

```
# lspci -v

 03:00.0 RAID bus controller: LSI Logic / Symbios Logic MegaRAID SAS 2108 [Liberator]
(rev 05)

        Subsystem: Dell PERC H700 Integrated

        Flags: bus master, fast devsel, latency 0, IRQ 16

        I/O ports at fc00 [size=256]

        Memory at df1bc000 (64-bit, non-prefetchable) [size=16K]

        Memory at df1c0000 (64-bit, non-prefetchable) [size=256K]

        Expansion ROM at df100000 [disabled] [size=256K]

        Capabilities: [50] Power Management version 3
```

Display Device Codes in the Output

If you want to display the PCI vendor code, and the device code only as the numbers, use -n option. This will not lookup the PCI file to get the corresponding values for the numbers.

```
# lspci -n

01:00.1 0200: 14e4:1639 (rev 20)

02:00.0 0200: 14e4:1639 (rev 20)

02:00.1 0200: 14e4:1639 (rev 20)

03:00.0 0104: 1000:0079 (rev 05)

06:03.0 0300: 102b:0532 (rev 0a)
```

If you want to display both the description and the number, use the option -nn as shown below.

```
# lspci -nn
```

Lookup a Specific Device

When you know the slot number in the domain:bus:slot.func format, you can query for a particular device as shown below. In the following example, we didn't specify the domain number, as it is 0, which can be left out.

```
# lspci -s 03:00.0

03:00.0 RAID bus controller: LSI Logic / Symbios Logic MegaRAID SAS 2108 [Liberator]
(rev 05)
```

When you know the device number in the vendor:device format, you can query for a particular device as shown below.

```
# lspci -d 1000:0079

03:00.0 RAID bus controller: LSI Logic / Symbios Logic MegaRAID SAS 2108 [Liberator]
(rev 05)
```

If you know only either the vendor id, or the device id, you can omit the other id. For example, both the following command will return the same output as the above.

Display Kernel Drivers

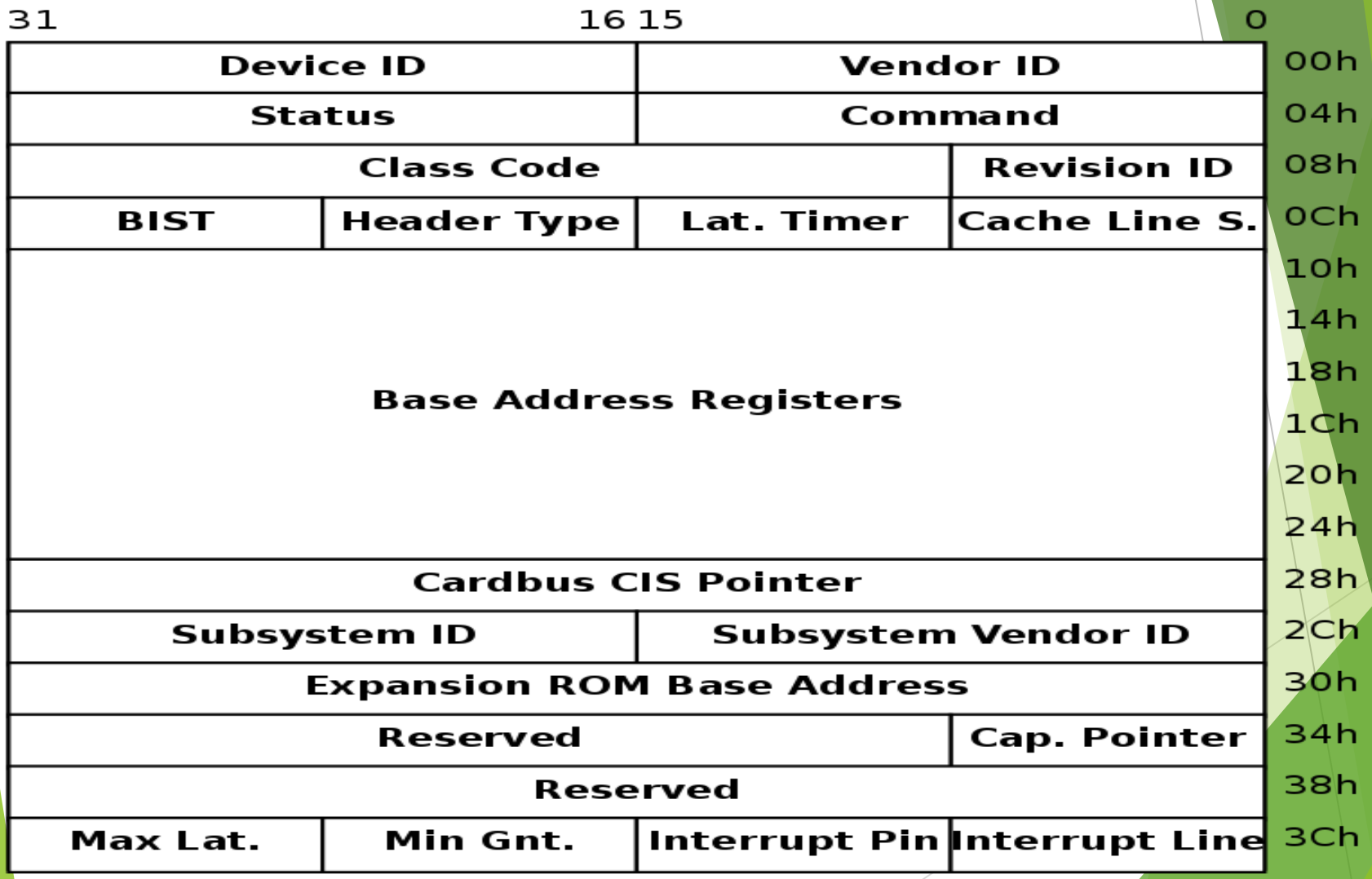
This is very helpful when you like to know the name of the kernel module that will be handling the operations of a particular device. Please note that this option will work only on Kernel 2.6 version and above.

```
# lspci -k

00:1f.2 IDE interface: Intel Corporation 82801IB (ICH9) 2 port SATA Controller [IDE
mode] (rev 02)

        Subsystem: Dell PowerEdge R610 SATA IDE Controller

        Kernel driver in use: ata_piix

        Kernel modules: ata_generic, pata_acpi, ata_piix

02:00.0 Ethernet controller: Broadcom Corporation NetXtreme II BCM5709 Gigabit
Ethernet (rev 20)

        Subsystem: Dell PowerEdge R610 BCM5709 Gigabit Ethernet

        Kernel driver in use: bnx2
```

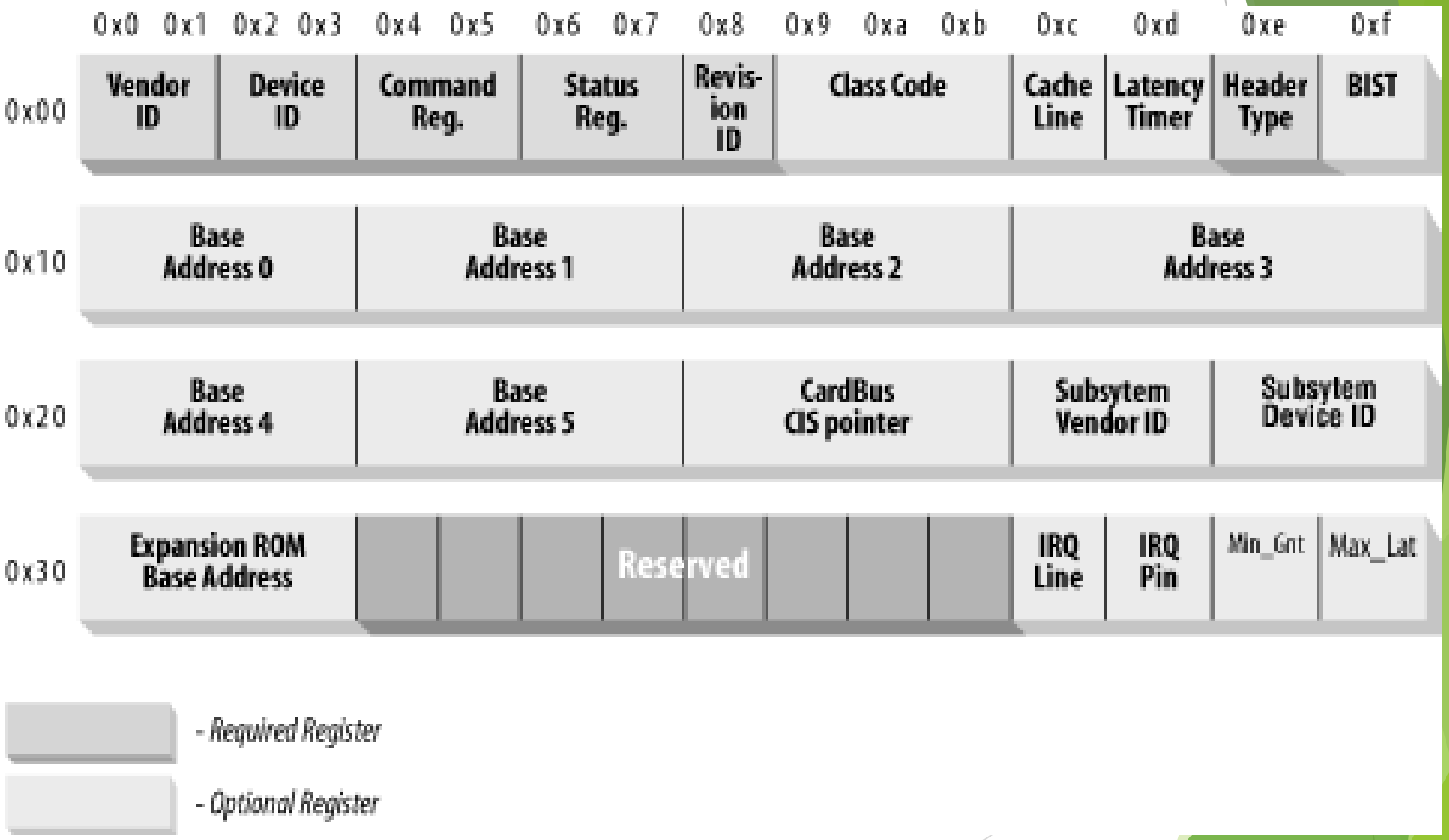
PCI Configuration Space

PCI devices have a set of registers referred to as *configuration space* and PCI Express introduces *extended configuration space* for devices. Configuration space registers are mapped to memory locations. Device drivers and diagnostic software must have access to the configuration space, and operating systems typically use APIs to allow access to device configuration space. When the operating system does not have access methods defined or APIs for memory mapped configuration space requests, the driver or diagnostic software has the burden to access the configuration space in a manner that is compatible with the operating system's underlying access rules. In all systems, device drivers are encouraged to use APIs provided by the operating system to access the configuration space of the device.

PCI Configuration Space



PCI Configuration Space



Features for driver-writers

Support for “auto-detection” of devices

Device configuration is “programmable”

Introduces “PCI Configuration Space”

A nonvolatile data-structure of device info

A standard “header” layout: 64 longwords

Linux provides some interface functions:

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

struct pci_device_id

The struct pci_device_id structure is used to define a list of the different types of PCI devices that a driver supports. This structure contains the following fields:

_ _u32 vendor;

_ _u32 device;

These specify the PCI vendor and device IDs of a device. If a driver can handle any vendor or device ID, the value PCI_ANY_ID should be used for these fields.

_ _u32 subvendor;

_ _u32 subdevice;

These specify the PCI subsystem vendor and subsystem device IDs of a device. If a driver can handle any type of subsystem ID, the value PCI_ANY_ID should be used for these fields.

struct pci_device_id

_ _u32 class;

_ _u32 class_mask;

These two values allow the driver to specify that it supports a type of PCI class device. The different classes of PCI devices (a VGA controller is one example) are described in the PCI specification. If a driver can handle any type of subsystem ID, the value PCI_ANY_ID should be used for these fields.

kernel_ulong_t driver_data;

This value is not used to match a device but is used to hold information that the PCI driver can use to differentiate between different devices if it wants to.

struct pci_device_id

There are two helper macros that should be used to initialize a struct pci_device_id structure:

PCI_DEVICE(vendor, device)

This creates a struct pci_device_id that matches only the specific vendor and device ID. The macro sets the subvendor and subdevice fields of the structure to PCI_ANY_ID.

PCI_DEVICE_CLASS(device_class, device_class_mask)

This creates a struct pci_device_id that matches a specific PCI class.

struct pci_device_id

An example of using these macros to define the type of devices a driver supports can be found in the following kernel files:

drivers/usb/host/ehci-hcd.c:

```
static const struct pci_device_id pci_ids[  ] = { {
        /* handle any USB 2.0 EHCI controller */
        PCI_DEVICE_CLASS(((PCI_CLASS_SERIAL_USB << 8) | 0x20), ~0),
        .driver_data =  (unsigned long) &ehci_driver,
        },
        { /* end: all zeroes */ }
};
```

drivers/i2c/busses/i2c-i810.c:

```
static struct pci_device_id i810_ids[  ] = {
    { PCI_DEVICE(PCI_VENDOR_ID_INTEL, PCI_DEVICE_ID_INTEL_82810_IG1) },
    { PCI_DEVICE(PCI_VENDOR_ID_INTEL, PCI_DEVICE_ID_INTEL_82810_IG3) },
    { PCI_DEVICE(PCI_VENDOR_ID_INTEL, PCI_DEVICE_ID_INTEL_82810E_IG) },
    { PCI_DEVICE(PCI_VENDOR_ID_INTEL, PCI_DEVICE_ID_INTEL_82815_CGC) },
    { PCI_DEVICE(PCI_VENDOR_ID_INTEL, PCI_DEVICE_ID_INTEL_82845G_IG) },
    { 0, },
};
```

MODULE_DEVICE_TABLE

This pci_device_id structure needs to be exported to user space to allow the hotplug and module loading systems know what module works with what hardware devices. The macro MODULE_DEVICE_TABLE accomplishes this. An example is:

MODULE_DEVICE_TABLE(pci, i810_ids);

Registering a PCI Driver

The main structure that all PCI drivers must create in order to be registered with the kernel properly is the struct pci_driver structure. This structure consists of a number of function callbacks and variables that describe the PCI driver to the PCI core. Here are the fields in this structure that a PCI driver needs to be aware of:

const char *name;

The name of the driver. It must be unique among all PCI drivers in the kernel and is normally set to the same name as the module name of the driver. It shows up in sysfs under /sys/bus/pci/drivers/ when the driver is in the kernel.

const struct pci_device_id *id_table;

Pointer to the struct pci_device_id table

Registering a PCI Driver

int (*probe) (struct pci_dev *dev, const struct pci_device_id *id);

Pointer to the probe function in the PCI driver. This function is called by the PCI core when it has a struct pci_dev that it thinks this driver wants to control. A pointer to the struct pci_device_id that the PCI core used to make this decision is also passed to this function. If the PCI driver claims the struct pci_dev that is passed to it, it should initialize the device properly and return 0. If the driver does not want to claim the device, or an error occurs, it should return a negative error value. More details about this function follow later in this chapter.

void (*remove) (struct pci_dev *dev);

Pointer to the function that the PCI core calls when the struct pci_dev is being removed from the system, or when the PCI driver is being unloaded from the kernel. More details about this function follow later in this chapter.

Registering a PCI Driver

int (*suspend) (struct pci_dev *dev, u32 state);

Pointer to the function that the PCI core calls when the struct pci_dev is being suspended. The suspend state is passed in the state variable. This function is optional; a driver does not have to provide it.

int (*resume) (struct pci_dev *dev);

Pointer to the function that the PCI core calls when the struct pci_dev is being resumed. It is always called after suspend has been called. This function is optional; a driver does not have to provide it.

Registering a PCI Driver

In summary, to create a proper `struct pci_driver` structure, only four fields need to be initialized:

```
static struct pci_driver pci_driver = {
    .name = "pci_skel",
    .id_table = ids,
    .probe = probe,
    .remove = remove,
};
```

To register the `struct pci_driver` with the PCI core, a call to *pci_register_driver* is made with a pointer to the `struct pci_driver`. This is traditionally done in the module initialization code for the PCI driver:

```
static int _ _init pci_skel_init(void)
{
    return pci_register_driver(&pci_driver);
}
```

UnRegistering a PCI Driver

When the PCI driver is to be unloaded, the struct pci_driver needs to be unregistered from the kernel. This is done with a call to pci_unregister_driver. When this call happens, any PCI devices that were currently bound to this driver are removed, and the remove function for this PCI driver is called before the pci_unregister_driver function returns.

```
static void _ _exit pci_skel_exit(void)
{
    pci_unregister_driver(&pci_driver);
}
```

Enabling the PCI Device

In the probe function for the PCI driver, before the driver can access any device resource (I/O region or interrupt) of the PCI device, the driver must call the pci_enable_device function:

int pci_enable_device(struct pci_dev *dev);

This function actually enables the device. It wakes up the device and in some cases also assigns its interrupt line and I/O regions. This happens, for example, with CardBus devices (which have been made completely equivalent to PCI at the driver level).

Accessing the Configuration Space

After the driver has detected the device, it usually needs to read from or write to the three address spaces: memory, port, and configuration. In particular, accessing the configuration space is vital to the driver, because it is the only way it can find out where the device is mapped in memory and in the I/O space.

As far as the driver is concerned, the configuration space can be accessed through 8-bit, 16-bit, or 32-bit data transfers. The relevant functions are prototyped in <linux/pci.h>:

```
int pci_read_config_byte(struct pci_dev *dev, int where, u8 *val);
int pci_read_config_word(struct pci_dev *dev, int where, u16 *val);
int pci_read_config_dword(struct pci_dev *dev, int where, u32 *val);
```

Accessing the Configuration Space

```
int pci_write_config_byte(struct pci_dev *dev, int where, u8 val);
int pci_write_config_word(struct pci_dev *dev, int where, u16 val);
int pci_write_config_dword(struct pci_dev *dev, int where, u32 val);
```

Accessing the Configuration Space

```
int pci_write_config_byte(struct pci_dev *dev, int where, u8 val);
int pci_write_config_word(struct pci_dev *dev, int where, u16 val);
int pci_write_config_dword(struct pci_dev *dev, int where, u32 val);
```

Accessing the I/O and Memory Spaces

The preferred interface for getting region information consists of the following functions:

unsigned long pci_resource_start(struct pci_dev *dev, int bar);

The function returns the first address (memory address or I/O port number) associated with one of the six PCI I/O regions. The region is selected by the integer bar (the base address register), ranging from 0-5 (inclusive).

unsigned long pci_resource_end(struct pci_dev *dev, int bar);

The function returns the last address that is part of the I/O region number bar. Note that this is the last usable address, not the first address after the region.

Accessing the I/O and Memory Spaces

unsigned long pci_resource_flags(struct pci_dev *dev, int bar);

This function returns the flags associated with this resource.

All resource flags are defined in <linux/ioport.h>; the most important are:

IORESOURCE_IO

IORESOURCE_MEM

If the associated I/O region exists, one and only one of these flags is set.

IORESOURCE_PREFETCH

IORESOURCE_READONLY

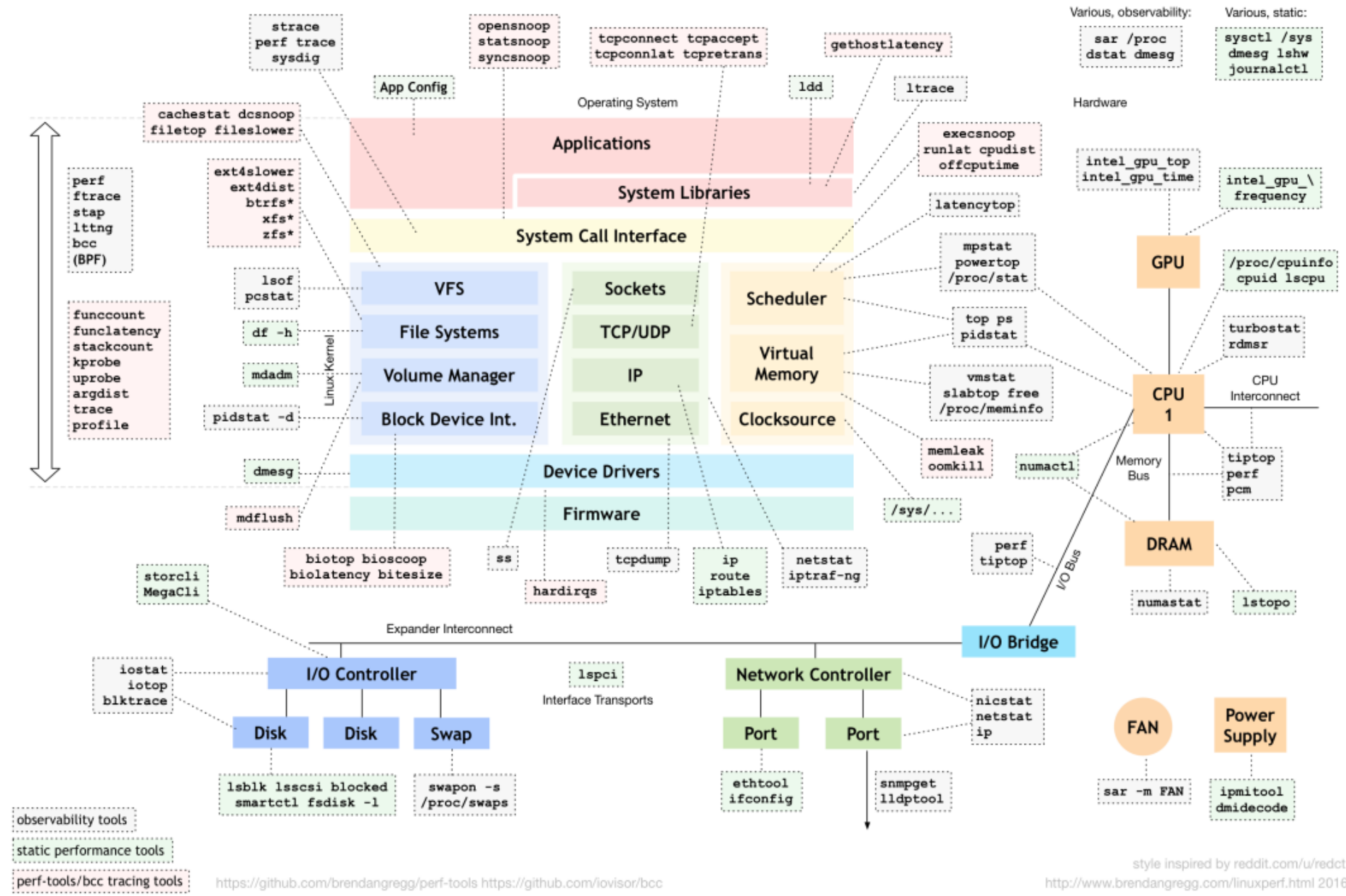
These flags tell whether a memory region is prefetchable and/or write protected. The latter flag is never set for PCI resources.

PCI Interrupt

```
result = pci_read_config_byte(dev, PCI_INTERRUPT_LINE, &myirq);
if (result) {
    /* deal with error */
}
```

Kernel Debugging

Linux Performance Tools



Syslog

Syslog is a known standard for message logging. Most times, the system that does the logging and the software that gets to generate them tend to interfere during processes. But syslog helps separate the software generating the logs from the system that stores the logs, thereby making the process of logging less complicated and stressful.

- **Syslog Daemon**: It is a daemon that listens for logs and writes them to a specific location. The location(s) is defined in the configuration file for the daemon. rsyslog is the Syslog daemon shipped with most of the distros.

- **Syslog Message Format**: It refers to the syntax of Syslog messages. The syntax is usually defined by a standard (for eg RFC5424).

Syslog

- **Syslog Protocol**: It refers to the protocol used for remote logging. Modern Syslog daemons can use TCP and TLS in addition to UDP which is the legacy protocol for remote logging.

Syslog

Benefits of syslog

- Helps analyze the root cause for any trouble or problem caused
- Reduce overall downtime helping to troubleshoot issues faster with all the logs
- Improves incident management by active detection of issues
- Self-determination of incidents along with auto resolution
- Simplified architecture with different level of severity like error,info,warning etc

Syslog

Display syslogs with the ls command

Listing the contents of /var/log for an Ubuntu 20.04 machine using the ls command:

$ sudo ls /var/log

```
test@test-VirtualBox:~$ sudo ls /var/log
[sudo] password for test:
alternatives.log       auth.log.3.gz  dmesg           journal            syslog.5.gz
alternatives.log.1     auth.log.4.gz  dmesg.0         kern.log           syslog.6.gz
alternatives.log.2.gz  boot.log       dmesg.1.gz      kern.log.1         syslog.7.gz
apport.log             boot.log.1     dmesg.2.gz      kern.log.2.gz      ubuntu-advantage.log
apport.log.1           boot.log.2     dmesg.3.gz      kern.log.3.gz      ubuntu-advantage.log.1
apport.log.2.gz        boot.log.3     dmesg.4.gz      kern.log.4.gz      ubuntu-advantage.log.2.gz
apport.log.3.gz        boot.log.4     dpkg.log        lastlog            unattended-upgrades
apport.log.4.gz        boot.log.5     dpkg.log.1      openvpn            vboxadd-install.log
apport.log.5.gz        boot.log.6     dpkg.log.2.gz   private            vboxadd-setup.log
apport.log.6.gz        boot.log.7     faillog         speech-dispatcher  vboxadd-setup.log.1
apport.log.7.gz        bootstrap.log  fontconfig.log  syslog             vboxadd-setup.log.2
apt                    btmp           gdm3            syslog.1           vboxadd-setup.log.3
auth.log               btmp.1         gpu-manager.log syslog.2.gz        vboxadd-setup.log.4
auth.log.1             cups           hp              syslog.3.gz        vboxadd-uninstall.log
auth.log.2.gz          dist-upgrade   installer       syslog.4.gz        wtmp
test@test-VirtualBox:~$
```

Syslog

View system logs in Linux using the tail command

Using the tail command you can view the last few logs. Adding the -f option lets you watch them in real time.

$ sudo tail -f /var/log/syslog

Similarly, the tail command can be used to view kernel logs (kern.log), boot logs (boot.log), etc .

Syslog

Syslog Configuration

The rules for which logs go where are defined in the Syslog daemon's configuration file.

$ sudo vi /etc/rsyslog.conf

$ sudo vi /etc/rsyslog.d/50-default.conf

```
#  Default rules for rsyslog.
#
#                       For more information see rsyslog.conf(5) and /etc/rsyslog.conf

#
# First some standard log files.  Log by facility.
#
auth,authpriv.*                 /var/log/auth.log
*.*;auth,authpriv.none          -/var/log/syslog
#cron.*                         /var/log/cron.log
#daemon.*                       -/var/log/daemon.log
kern.*                          -/var/log/kern.log
#lpr.*                          -/var/log/lpr.log
mail.*                          -/var/log/mail.log
#user.*                         -/var/log/user.log
local1.*                        -/var/log/test41.log
```

ftrace

Ftrace is a tracing framework for the Linux kernel. It was added to the kernel back in 2008 and has evolved a lot since then.

Ftrace stands for function tracer and basically lets you watch and record the execution flow of kernel functions. It was created by Steven Rostedt, derived from two other tools called latency tracer from Ingo Molnar and Steven’s logdev utility.

ftrace

With ftrace you can really see what the kernel is doing. You can trace function calls and learn a lot about how the kernel works. You can find out which kernel functions are called when you run a user space application. You can profile functions, measure execution time and find out bottlenecks and performance issues. You can identify hangs in kernel space. You can measure the time it takes to run a real-time task and find out latency issues. You can measure stack usage in kernel space and find out possible stack overflows. You can really do a lot of things to monitor and find bugs in the kernel!

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ftrace

And this is the filesystem interface provided by ftrace:

```
# ls /sys/kernel/tracing/
README                      set_ftrace_filter
available_events            set_ftrace_notrace
available_filter_functions  set_ftrace_pid
available_tracers           set_graph_function
buffer_size_kb              set_graph_notrace
buffer_total_size_kb        snapshot
current_tracer              stack_max_size
dyn_ftrace_total_info       stack_trace
enabled_functions           stack_trace_filter
events                      timestamp_mode
free_buffer                 trace
function_profile_enabled    trace_clock
hwlat_detector              trace_marker
instances                   trace_marker_raw
max_graph_depth             trace_options
options                     trace_pipe
per_cpu                     trace_stat
printk_formats              tracing_cpumask
saved_cmdlines              tracing_max_latency
saved_cmdlines_size         tracing_on
saved_tgids                 tracing_thresh
set_event                   uprobe_events
set_event_pid               uprobe_profile
```

ftrace

We can print the list of available tracers:

```
# cat available_tracers
hwlat   blk      function_graph   wakeup_dl   wakeup_rt
wakeup  irqsoff  function         nop
```

There are function tracers (*function*, *function_graph*), latency tracers (*wakeup_dl*, *wakeup_rt*, *irqsoff*, *wakeup*, *hwlat*), I/O tracers (*blk*) and many more!

To enable a tracer, we just have to write its name to *current_tracer*:

```
# echo function > current_tracer
```

ftrace

And we can read the trace buffer with the *trace* or *trace_pipe* file:

```
# cat trace
# tracer: function
#
#                              _-----=> irqs-off
#                             / _----=> need-resched
#                            | / _---=> hardirq/softirq
#                            || / _--=> preempt-depth
#                            ||| /     delay
#           TASK-PID   CPU#  ||||    TIMESTAMP  FUNCTION
#              | |       |   ||||       |         |
          <idle>-0     [001] d...    23.695208: _raw_spin_lock_irqsave <-hrtimer_next_event_wi...
          <idle>-0     [001] d...    23.695209: __hrtimer_next_event_base <-hrtimer_next_event...
          <idle>-0     [001] d...    23.695210: __next_base <-__hrtimer_next_event_base
          <idle>-0     [001] d...    23.695211: __hrtimer_next_event_base <-hrtimer_next_event...
          <idle>-0     [001] d...    23.695212: __next_base <-__hrtimer_next_event_base
          <idle>-0     [001] d...    23.695213: __next_base <-__hrtimer_next_event_base
          <idle>-0     [001] d...    23.695214: _raw_spin_unlock_irqrestore <-hrtimer_next_eve...
          <idle>-0     [001] d...    23.695215: get_iowait_load <-menu_select
          <idle>-0     [001] d...    23.695217: tick_nohz_tick_stopped <-menu_select
          <idle>-0     [001] d...    23.695218: tick_nohz_idle_stop_tick <-do_idle
          <idle>-0     [001] d...    23.695219: rcu_idle_enter <-do_idle
          <idle>-0     [001] d...    23.695220: call_cpuidle <-do_idle
          <idle>-0     [001] d...    23.695221: cpuidle_enter <-call_cpuidle
```

ftrace

The function graph tracer is an alternative function tracer that traces not only the function entry but also the return of the function, allowing you to create a call graph of the function flow and output the trace data in a C-like style with information about the duration of each function.

```
# echo function_graph > current_tracer

# cat trace
# tracer: function_graph
#
# CPU  DURATION                  FUNCTION CALLS
# |     |   |                     |   |   |   |
 0)   1.000 us    |                } /* idle_cpu */
 0)               |                tick_nohz_irq_exit() {
 0)               |                  ktime_get() {
 0)   1.000 us    |                    clocksource_mmio_readl_up();
 0)   7.666 us    |                  }
 0) + 14.000 us   |                }
 0)               |                rcu_irq_exit() {
 0)   1.334 us    |                  rcu_nmi_exit();
 0)   7.667 us    |                }
 0) ! 556.000 us  |              } /* irq_exit */
 0) # 1187.667 us |            } /* __handle_domain_irq */
 0) # 1194.333 us |          } /* gic_handle_irq */
 0)   <========== |
 0) # 8197.333 us |        } /* cpuidle_enter_state */
 0) # 8205.334 us |      } /* cpuidle_enter */
[...]
```

Trace-cmd

trace-cmd is a user-space command-line tool for ftrace created by Steven Rostedt.

It is a front-end to the tracefs filesystem and can be used to configure ftrace, read the trace buffer and save the data to a file (*trace.dat* by default) for further analysis.

```
# trace-cmd

trace-cmd version 2.6.1

usage:
  trace-cmd [COMMAND] ...

  commands:
     record - record a trace into a trace.dat file
     start - start tracing without recording into a file
     extract - extract a trace from the kernel
     stop - stop the kernel from recording trace data
     restart - restart the kernel trace data recording
     show - show the contents of the kernel tracing buffer
     reset - disable all kernel tracing and clear the trace buffers
     report - read out the trace stored in a trace.dat file
     stream - Start tracing and read the output directly
     profile - Start profiling and read the output directly
     hist - show a historgram of the trace.dat information
     stat - show the status of the running tracing (ftrace) system
     split - parse a trace.dat file into smaller file(s)
     options - list the plugin options available for trace-cmd report
     listen - listen on a network socket for trace clients
     list - list the available events, plugins or options
     restore - restore a crashed record
     snapshot - take snapshot of running trace
```

Trace-cmd

For example, the command below will start a function tracing:

```
# trace-cmd start -p function
```

And the command below will trace GPIO events:

```
# trace-cmd start -e gpio
```

We can also trace a specific process and record the tracing data to a file:

```
# trace-cmd record -p function -F ls /
  plugin 'function'
CPU0 data recorded at offset=0x30d000
    737280 bytes in size
CPU1 data recorded at offset=0x3c1000
    0 bytes in size

# ls trace.dat
trace.dat
```

Trace-cmd

We can show the tracing data with the *report* command:

```
# trace-cmd report
CPU 1 is empty
cpus=2
             ls-175   [000]    43.359618: function:             mutex_unlock <-- rb_simple_write
             ls-175   [000]    43.359624: function:             __fsnotify_parent <-- vfs_write
             ls-175   [000]    43.359625: function:             fsnotify <-- vfs_write
             ls-175   [000]    43.359627: function:             __sb_end_write <-- vfs_write
```

Or we can open it with **KernelShark**.

KernelShark

KernelShark is a graphical tool that works as a frontend to the *trace.dat* file generated by the *trace-cmd* tool.

Printk

dmesg command is used to display the kernel related messages on Unix like systems. dmesg stands for “display message or display driver“. dmesg command retrieve its data by reading the kernel ring buffer. While doing troubleshooting on Linux systems, dmesg command becomes very handy, it can help us to identify hardware related errors and warnings, apart from this it can print daemon related messages on your screen.

In this article we will cover 10 useful tips about dmesg command for Linux administrators or geeks, Below is the syntax of dmesg command,

 # dmesg {options}

Printk

Following are the options that can be used in dmesg command

1. Display all messages from kernel ring buffer

Open the terminal and type ‘dmesg’ command and then hit enter. On your screen you will get all the messages from kernel ring buffer.

~]# dmesg

Printk

dmesg command will print all messages but you will only see the latest message that fits on screen, if you want to do the analysis all the logs and display them as page wise then use less or more command,

~]# dmesg | less

Printk

Display messages related to RAM, Hard disk, USB drives and Serial ports

In dmesg command output we can search the messages related to RAM, Hard disk , usb drive and Serial ports.

~]# dmesg | grep -i memory

~]# dmesg | grep -i dma

~]# dmesg | grep -i usb

~]# dmesg | grep -i tty

Printk

These above commands can be merged into a single command using multiple grep option (-E), examples is shown below,

~]# dmesg | grep -E "memory|dma|usb|tty"

Read and Clear dmesg logs using (-C) option

If you want to clear dmesg logs after the reading them, then you can use the option -C in dmesg command,

~]# dmesg -C

Printk

Display colored messages (dmesg command output)

Use ‘-L’ option in dmesg command if you want to print the colored messages,

~]# dmesg –L

5. Limit the dmesg output to specific facility like daemon

If you want to limit the dmesg output to specific facility like daemon then use the option “–facility=daemon” in dmesg command,

~]# dmesg --facility=daemon

Printk

Restrict dmesg command output to specific list of levels

Following are specific log levels supported by dmesg command,

emerg

alert

crit

err

warn

notice

info

debug

Let's assume we want to display logs related to error and warning, then use "–level" option followed by levels like err & warn, example is shown below

~]# dmesg --level=err,warn

Printk

Enable timestamps in dmesg logs

There can be some scenarios where we want to enable timestamps in dmesg, this can be easily achieved by using '-T' option in dmesg command.

~]# dmesg -T

Monitor real time dmesg logs using '–follow' option

Use '–follow' option in dmesg command to view real time dmesg logs, example is shown below,

~]# dmesg --follow

Printk

Display raw message buffer using ‘-r’ option

Use ‘-r’ option in dmesg command to display raw message buffer, example is shown below,

~]# dmesg -r

Force dmesg command to use syslog

There can be some situations where we want dmesg to get its data from syslog rather than /dev/kmsg. This can be easily achieved using the option “-S“, example is shown below:

~]# dmesg -S

Printk

 # echo "sample log message" >/dev/kmsg

 # dmesg | tail

Debugging Support in the Kernel

Here, we list the configuration options that should be enabled for kernels used for development. Except where specified otherwise, all of these options are found under the “kernel hacking” menu in whatever kernel configuration tool you prefer. Note that some of these options are not supported by all architectures.

CONFIG_DEBUG_KERNEL

This option just makes other debugging options available; it should be turned on but does not, by itself, enable any features.

Debugging Support in the Kernel

CONFIG_DEBUG_SLAB

This crucial option turns on several types of checks in the kernel memory allocation functions; with these checks enabled, it is possible to detect a number of memory overrun and missing initialization errors. Each byte of allocated memory is set to 0xa5 before being handed to the caller and then set to 0x6b when it is freed. If you ever see either of those “poison” patterns repeating in output from your driver (or often in an oops listing), you’ll know exactly what sort of error to look for. When debugging is enabled, the kernel also places special guard values before and after every allocated memory object; if those values ever get changed, the kernel knows that somebody has overrun a memory allocation, and it complains loudly. Various checks for more obscure errors are enabled as well.

Debugging Support in the Kernel

CONFIG_DEBUG_PAGEALLOC

Full pages are removed from the kernel address space when freed. This option can slow things down significantly, but it can also quickly point out certain kinds of memory corruption errors.

CONFIG_DEBUG_SPINLOCK

With this option enabled, the kernel catches operations on uninitialized spinlocks and various other errors (such as unlocking a lock twice).

Debugging Support in the Kernel

CONFIG_DEBUG_SPINLOCK_SLEEP

This option enables a check for attempts to sleep while holding a spinlock. In fact, it complains if you call a function that could potentially sleep, even if the call in question would not sleep.

CONFIG_INIT_DEBUG

Items marked with _ _init (or _ _initdata) are discarded after system initialization or module load time. This option enables checks for code that attempts to access initialization-time memory after initialization is complete.

Debugging Support in the Kernel

CONFIG_DEBUG_INFO

This option causes the kernel to be built with full debugging information included. You'll need that information if you want to debug the kernel with gdb. You may also want to enable CONFIG_FRAME_POINTER if you plan to use gdb.

CONFIG_MAGIC_SYSRQ

Enables the "magic SysRq" key.

Debugging Support in the Kernel

CONFIG_DEBUG_STACKOVERFLOW

CONFIG_DEBUG_STACK_USAGE

These options can help track down kernel stack overflows. A sure sign of a stack overflow is an oops listing without any sort of reasonable back trace. The first option adds explicit overflow checks to the kernel; the second causes the kernel to monitor stack usage and make some statistics available via the magic SysRq key.

Debugging Support in the Kernel

CONFIG_KALLSYMS

This option (under “General setup/Standard features”) causes kernel symbol information to be built into the kernel; it is enabled by default. The symbol information is used in debugging contexts; without it, an oops listing can give you a kernel traceback only in hexadecimal, which is not very useful.

Debugging Support in the Kernel

CONFIG_IKCONFIG

CONFIG_IKCONFIG_PROC

These options (found in the “General setup” menu) cause the full kernel configuration state to be built into the kernel and to be made available via /proc. Most kernel developers know which configuration they used and do not need these options (which make the kernel bigger). They can be useful, though, if you are trying to debug a problem in a kernel built by somebody else.

Debugging Support in the Kernel

CONFIG_ACPI_DEBUG

Under “Power management/ACPI.” This option turns on verbose ACPI (Advanced Configuration and Power Interface) debugging information, which can be useful if you suspect a problem related to ACPI.

CONFIG_DEBUG_DRIVER

Under “Device drivers.” Turns on debugging information in the driver core, which can be useful for tracking down problems in the low-level support code.

Debugging Support in the Kernel

CONFIG_SCSI_CONSTANTS

This option, found under “Device drivers/SCSI device support,” builds in information for verbose SCSI error messages. If you are working on a SCSI driver, you probably want this option.

CONFIG_INPUT_EVBUG

This option (under “Device drivers/Input device support”) turns on verbose logging of input events. If you are working on a driver for an input device, this option may be helpful. Be aware of the security implications of this option, however: it logs everything you type, including your passwords.

Debugging Support in the Kernel

CONFIG_PROFILING

This option is found under “Profiling support.” Profiling is normally used for system performance tuning, but it can also be useful for tracking down some kernel hangs and related problems.

Debugging Support in the Kernel

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Rate Limiting

If you are not careful, you can find yourself generating thousands of messages with printk, overwhelming the console and, possibly, overflowing the system log file. When using a slow console device (e.g., a serial port), an excessive message rate can also slow down the system or just make it unresponsive. It can be very hard to get a handle on what is wrong with a system when the console is spewing out data nonstop. Therefore, you should be very careful about what you print, especially in production versions of drivers and especially once initialization is complete. In general, production code should never print anything during normal operation; printed output should be an indication of an exceptional situation requiring attention.

Rate Limiting

On the other hand, you may want to emit a log message if a device you are driving stops working. But you should be careful not to overdo things. An unintelligent process that continues forever in the face of failures can generate thousands of retries per second; if your driver prints a “my device is broken” message every time, it could create vast amounts of output and possibly hog the CPU if the console device is slow—no interrupts can be used to driver the console, even if it is a serial port or a line printer.

Rate Limiting

In many cases, the best behavior is to set a flag saying, “I have already complained about this,” and not print any further messages once the flag gets set. In others, though, there are reasons to emit an occasional “the device is still broken” notice. The kernel has provided a function that can be helpful in such cases:

int printk_ratelimit(void);

This function should be called before you consider printing a message that could be repeated often. If the function returns a nonzero value, go ahead and print your message, otherwise skip it. Thus, typical calls look like this:

```
if (printk_ratelimit( ))
    printk(KERN_NOTICE "The printer is still on fire\n");
```

Rate Limiting

printk_ratelimit works by tracking how many messages are sent to the console. When the level of output exceeds a threshold, printk_ratelimit starts returning 0 and causing messages to be dropped.

The behavior of printk_ratelimit can be customized by modifying **/proc/sys/kernel/printk_ratelimit** (the number of seconds to wait before re-enabling messages) and are **/proc/sys/kernel/printk_ratelimit_burst** (the number of messages accepted before rate-limiting).

Kernel OOPS

An “Oops” is what the kernel throws at us when it finds something faulty, or an exception, in the kernel code. It’s somewhat like the segfaults of user-space. An Oops dumps its message on the console; it contains the processor status and the CPU registers of when the fault occurred. The offending process that triggered this Oops gets killed without releasing locks or cleaning up structures. The system may not even resume its normal operations sometimes; this is called an unstable state. Once an Oops has occurred, the system cannot be trusted any further.

Kernel OOPS

The running kernel should be compiled with CONFIG_DEBUG_INFO, and syslogd should be running.

Kernel OOPS

```
[23960.488891] oops from the module
[23960.488899] BUG: kernel NULL pointer dereference, address: 0000000000000000
[23960.488902] #PF: supervisor write access in kernel mode
[23960.488905] #PF: error_code(0x0002) - not-present page
[23960.488906] PGD 0 P4D 0
[23960.488909] Oops: 0002 [#1] SMP PTI
[23960.488912] CPU: 0 PID: 10259 Comm: insmod Tainted: G           OE     5.11.0-27-generic #29~20.04.1-Ubuntu
[23960.488915] Hardware name: innotek GmbH VirtualBox/VirtualBox, BIOS VirtualBox 12/01/2006
[23960.488917] RIP: 0010:my_oops_init+0x17/0x1000 [koops1]
[23960.488923] Code: Unable to access opcode bytes at RIP 0xffffffffc0710fed.
[23960.488924] RSP: 0000:ffffaec5c491fc78 EFLAGS: 00010246
[23960.488927] RAX: 0000000000000000 RBX: 0000000000000000 RCX: 0000000000000000
[23960.488935] RDX: 0000000000000000 RSI: ffff9b5b5bc18ac0 RDI: ffff9b5b5bc18ac0
[23960.488936] RBP: ffffaec5c491fc78 R08: ffff9b5b5bc18ac0 R09: ffffaec5c491fa50
[23960.488938] R10: 0000000000000001 R11: 0000000000000001 R12: ffffffffc0711000
[23960.488939] R13: ffff9b5b4092e8e0 R14: 0000000000000000 R15: ffffaec5c491fe70
[23960.488941] FS:  00007f73e2974540(0000) GS:ffff9b5b5bc00000(0000) knlGS:0000000000000000
[23960.488943] CS:  0010 DS: 0000 ES: 0000 CR0: 0000000080050033
[23960.488945] CR2: ffffffffc0710fed CR3: 00000000c58c6006 CR4: 00000000000706f0
[23960.488949] Call Trace:
[23960.488952]  do_one_initcall+0x48/0x1d0
[23960.488957]  ? _cond_resched+0x19/0x30
[23960.488962]  ? kmem_cache_alloc_trace+0x380/0x430
[23960.488966]  ? do_init_module+0x28/0x250
[23960.488984]  do_init_module+0x62/0x250
[23960.488987]  load_module+0x11aa/0x1370
[23960.488991]  ? security_kernel_post_read_file+0x5c/0x70
[23960.488994]  ? security_kernel_post_read_file+0x5c/0x70
[23960.488999]  __do_sys_finit_module+0xc2/0x120
[23960.489002]  ? __do_sys_finit_module+0xc2/0x120
[23960.489006]  __x64_sys_finit_module+0x1a/0x20
[23960.489009]  do_syscall_64+0x38/0x90
[23960.489013]  entry_SYSCALL_64_after_hwframe+0x44/0xa9
[23960.489016] RIP: 0033:0x7f73e2ab989d
[23960.489018] Code: 00 c3 66 2e 0f 1f 84 00 00 00 00 00 90 f3 0f 1e fa 48 89 f8 48 89 f7 48 89 d6 48 89 ca 4d 89 c2 4d 89 c8 4c 8b 4c 24 08 0f 05 <48> 3d 01 f0 ff ff 73 01 c3 48 8b 0d c3 f5 0c 00 f7 d8
64 89 01 48
[23960.489021] RSP: 002b:00007ffe01fcae18 EFLAGS: 00000246 ORIG_RAX: 0000000000000139
[23960.489023] RAX: ffffffffffffffda RBX: 000055705edc57b0 RCX: 00007f73e2ab989d
[23960.489025] RDX: 0000000000000000 RSI: 000055705d937358 RDI: 0000000000000003
[23960.489026] RBP: 0000000000000000 R08: 0000000000000000 R09: 00007f73e2b8d260
[23960.489027] R10: 0000000000000003 R11: 0000000000000246 R12: 000055705d937358
```

Kernel OOPS

Understanding the Oops dump

Let’s have a closer look at the above dump, to understand some of the important bits of information.

BUG: kernel NULL pointer dereference, address: 0000000000000000

The first line indicates a pointer with a NULL value.

Kernel OOPS

RIP: 0010:my_oops_init+0x17/0x1000 [koops1]

IP is the instruction pointer.

Oops: 0002 [#1] SMP PTI

This is the error code value in hex. Each bit has a significance of its own:

bit 0 == 0 means no page found, 1 means a protection fault

bit 1 == 0 means read, 1 means write

bit 2 == 0 means kernel, 1 means user-mode

[#1] — this value is the number of times the Oops occurred. Multiple Oops can be triggered as a cascading effect of the first one.

Kernel OOPS

CPU: 0

This denotes on which CPU the error occurred.

PID: 10259 Comm: insmod Tainted: G OE 5.11.0-27-generic #29~20.04.1-Ubuntu

The Tainted flag points to G here. Each flag has its own meaning. A few other flags, and their meanings, picked up from kernel/panic.c:

Kernel OOPS

G — GPL module has been loaded.

P — Proprietary module has been loaded.

F — Module has been forcibly loaded.

S — SMP with a CPU not designed for SMP.

R — User forced a module unload.

M — System experienced a machine check exception.

B — System has hit bad_page.

U — Userspace-defined naughtiness.

A — ACPI table overridden.

W — Taint on warning.

Kernel OOPS

RIP: 0010:my_oops_init+0x17/0x1000 [koops1]

RIP is the CPU register containing the address of the instruction that is getting executed. 0010 comes from the code segment register. **my_oops_init+0x17/0x1000** is the <symbol> + the offset/length.

Kernel OOPS

RSP: 0000:ffffaec5c491fc78 EFLAGS: 00010246

RAX: 0000000000000000 RBX: 0000000000000000 RCX: 0000000000000000

RDX: 0000000000000000 RSI: ffff9b5b5bc18ac0 RDI: ffff9b5b5bc18ac0

RBP: ffffaec5c491fc78 R08: ffff9b5b5bc18ac0 R09: ffffaec5c491fa50

R10: 0000000000000001 R11: 0000000000000001 R12: ffffffffc0711000

R13: ffff9b5b4092e8e0 R14: 0000000000000000 R15: ffffaec5c491fe70

FS: 00007f73e2974540(0000) GS:ffff9b5b5bc00000(0000) knlGS:0000000000000000

CS: 0010 DS: 0000 ES: 0000 CR0: 0000000080050033

CR2: ffffffffc0710fed CR3: 00000000c58c6006 CR4: 0000000000706f0

This is a dump of the contents of some of the CPU registers.

Kernel OOPS

Call Trace:

do_one_initcall+0x48/0x1d0

? _cond_resched+0x19/0x30

? kmem_cache_alloc_trace+0x380/0x430

? do_init_module+0x28/0x250

do_init_module+0x62/0x250

load_module+0x11aa/0x1370

? security_kernel_post_read_file+0x5c/0x70

? security_kernel_post_read_file+0x5c/0x70

?__do_sys_finit_module+0xc2/0x120

? __do_sys_finit_module+0xc2/0x120

__x64_sys_finit_module+0x1a/0x20

do_syscall_64+0x38/0x90

entry_SYSCALL_64_after_hwframe+0x44/0xa9

The above is the call trace — the list of functions being called just before the Oops occurred.

Kernel OOPS

Code: 00 c3 66 2e 0f 1f 84 00 00 00 00 00 90 f3 0f 1e fa 48 89 f8 48 89 f7 48 89 d6 48 89 ca 4d 89 c2 4d 89 c8 4c 8b 4c 24 08 0f 05 <48> 3d 01 f0 ff ff 73 01 c3 48 8b 0d c3 f5 0c 00 f7 d8 64 89 01 48

The Code is a hex-dump of the section of machine code that was being run at the time the Oops occurred.

Kernel OOPS

Debugging an Oops dump

The first step is to load the offending module into the GDB debugger, as follows:

#gdb oops.ko

GNU gdb (GDB) Fedora (7.1-18.fc13)

Reading symbols from /code/oops/oops.ko...done.

Kernel OOPS

(gdb) disassemble my_oops_init

Dump of assembler code for function my_oops_init:

```
   0x000000000000003c <+0>:    callq  0x41 <my_oops_init+5>
   0x0000000000000041 <+5>:    push   %rbp
   0x0000000000000042 <+6>:    mov    $0x0,%rdi
   0x0000000000000049 <+13>:   mov    %rsp,%rbp
   0x000000000000004c <+16>:   callq  0x51 <my_oops_init+21>
   0x0000000000000051 <+21>:   xor    %eax,%eax
   0x0000000000000053 <+23>:   movl   $0x0,0x0
   0x000000000000005e <+34>:   pop    %rbp
   0x000000000000005f <+35>:   retq
```

End of assembler dump.

Kernel OOPS

Now, to pin point the actual line of offending code, we add the starting address and the offset. The offset is available in the same RIP instruction line. In our case, we are adding 0x000000000000003c + 0x015 = 0x0000000000000053. This points to the movl instruction.

(gdb) list *0x0000000000000053

KDUMP

A Kernel Crash Dump refers to a portion of the contents of volatile memory (RAM) that is copied to disk whenever the execution of the kernel is disrupted. The following events can cause a kernel disruption :

- Kernel Panic
- Non Maskable Interrupts (NMI)
- Machine Check Exceptions (MCE)
- Hardware failure
- Manual intervention

KDUMP

Kdump is an utility used to capture the system core dump in the event of system crashes.These captured core dumps can be used later to analyze the exact cause of the system failure and implement the necessary fix to prevent the crashes in future.

Kdump reserves a small portion of the memory for the secondary kernel called **crashkernel**.

This secondary or crash kernel is used the capture the core dump image whenever the system crashes.

KDUMP

Install Kdump Tools

First, install the kdump, which is part of kexec-tools package.

 # yum install kexec-tools

Set crashkernel in grub.conf

Once the package is installed, edit /boot/grub/grub.conf file and set the amount of memory to be reserved for the kdump crash kernel.

KDUMP

You can edit the /boot/grub/grub.conf for the value crashkernel and set it to either auto or user-specified value. It is recommended to use minimum of 128M for a machine with 2G memory or higher.

In the following example, look for the line that start with “kernel”, where it is set to “crashkernel=auto”.

KDUMP

 # vi /boot/grub/grub.conf

Configure Dump Location

Once the kernel crashes, the core dump can be captured to local filesystem or remote filesystem(NFS) based on the settings defined in /etc/kdump.conf (in SLES operating system the path is /etc/sysconfig/kdump).

This file is automatically created when the kexec-tools package is installed.

KDUMP

All the entries in this file will be commented out by default. You can uncomment the ones that are needed for your best options.

 # vi /etc/kdump.conf

KDUMP

Configure Core Collector

The next step is to configure the core collector in Kdump configuration file. It is important to compress the data captured and filter all the unnecessary information from the captured core file.

To enable the core collector, uncomment the following line that starts with core_collector.

core_collector makedumpfile -c --message-level 1 -d 31

KDUMP

makedumpfile specified in the core_collector actually makes a small DUMPFILE by compressing the data.

makedumpfile provides two DUMPFILE formats (the ELF format and the kdump-compressed format).

By default, makedumpfile makes a DUMPFILE in the kdump-compressed format.

The kdump-compressed format can be read only with the crash utility, and it can be smaller than the ELF format because of the compression support.

The ELF format is readable with GDB and the crash utility.

-c is to compresses dump data by each page

-d is the number of pages that are unnecessary and can be ignored.

KDUMP

If you uncomment the line #default shell then the shell is invoked if the kdump fails to collect the core. Then the administrator can manually take the core dump using makedumpfile commands.

Restart kdump Services

Once kdump is configured, restart the kdump services,

 # systemctl enable kdump.service

To start the service in the current session, use the following command:

 # systemctl start kdump.service

KDUMP

Testing kdump (manually trigger kdump)

To test the configuration, we can reboot the system with kdump enabled, and make sure that the service is running.

For example:

 # systemctl is-active kdump

active

KDUMP

Manually Trigger the Core Dump

You can manually trigger the core dump using the following commands:

echo 1 > /proc/sys/kernel/sysrq

echo c > /proc/sysrq-trigger

The server will reboot itself and the crash dump will be generated.

KDUMP

View the Core Files

Once the server is rebooted, you will see the core file is generated under /var/crash based on location defined in /var/crash.

You will see vmcore and vmcore-dmseg.txt file:

 # ls -lR /var/crash

KDUMP

Kdump analysis using crash

Crash utility is used to analyze the core file captured by kdump.

It can also be used to analyze the core files created by other dump utilities like netdump, diskdump, xendump.

You need to ensure the “kernel-debuginfo” package is present and it is at the same level as the kernel.

KDUMP

Launch the crash tool as shown below. After you this command, you will get a cash prompt, where you can execute crash commands:

 # crash /var/crash/127.0.0.1-2014-03-26-12\:24\:39/vmcore /usr/lib/debug/lib/modules/`uname –r`/vmlinux

crash>

KDUMP

View the Process when System Crashed

Execute ps command at the crash prompt, which will display all the running process when the system crashed.

crash> ps

View Swap space when System Crashed

Execute swap command at the crash prompt, which will display the swap space usage when the system crashed.

crash> swap

KDUMP

View IPCS when System Crashed

Execute ipcs command at the crash prompt, which will display the shared memory usage when the system crashed.

crash> ipcs

View IRQ when System Crashed

Execute irq command at the crash prompt, which will display the IRQ stats when the system crashed.

crash> irq -s

KDUMP

vtop – This command translates a user or kernel virtual address to its physical address.

foreach – This command displays data for multiple tasks in the system

waitq – This command displays all the tasks queued on a wait queue.

View the Virtual Memory when System Crashed

Execute vm command at the crash prompt, which will display the virtual memory usage when the system crashed.

crash> vm

KDUMP

View the Open Files when System Crashed

Execute files command at the crash prompt, which will display the open files when the system crashed.

crash> files

View System Information when System Crashed

Execute sys command at the crash prompt, which will display system information when the system crashed.

crash> sys

KDUMP

View the Open Files when System Crashed

Execute files command at the crash prompt, which will display the open files when the system crashed.

crash> files

View System Information when System Crashed

Execute sys command at the crash prompt, which will display system information when the system crashed.

crash> sys

KGDB

KProbes

Perf

Perf

perf_events is an event-oriented observability tool, which can help you solve advanced performance and troubleshooting functions. Questions that can be answered include:

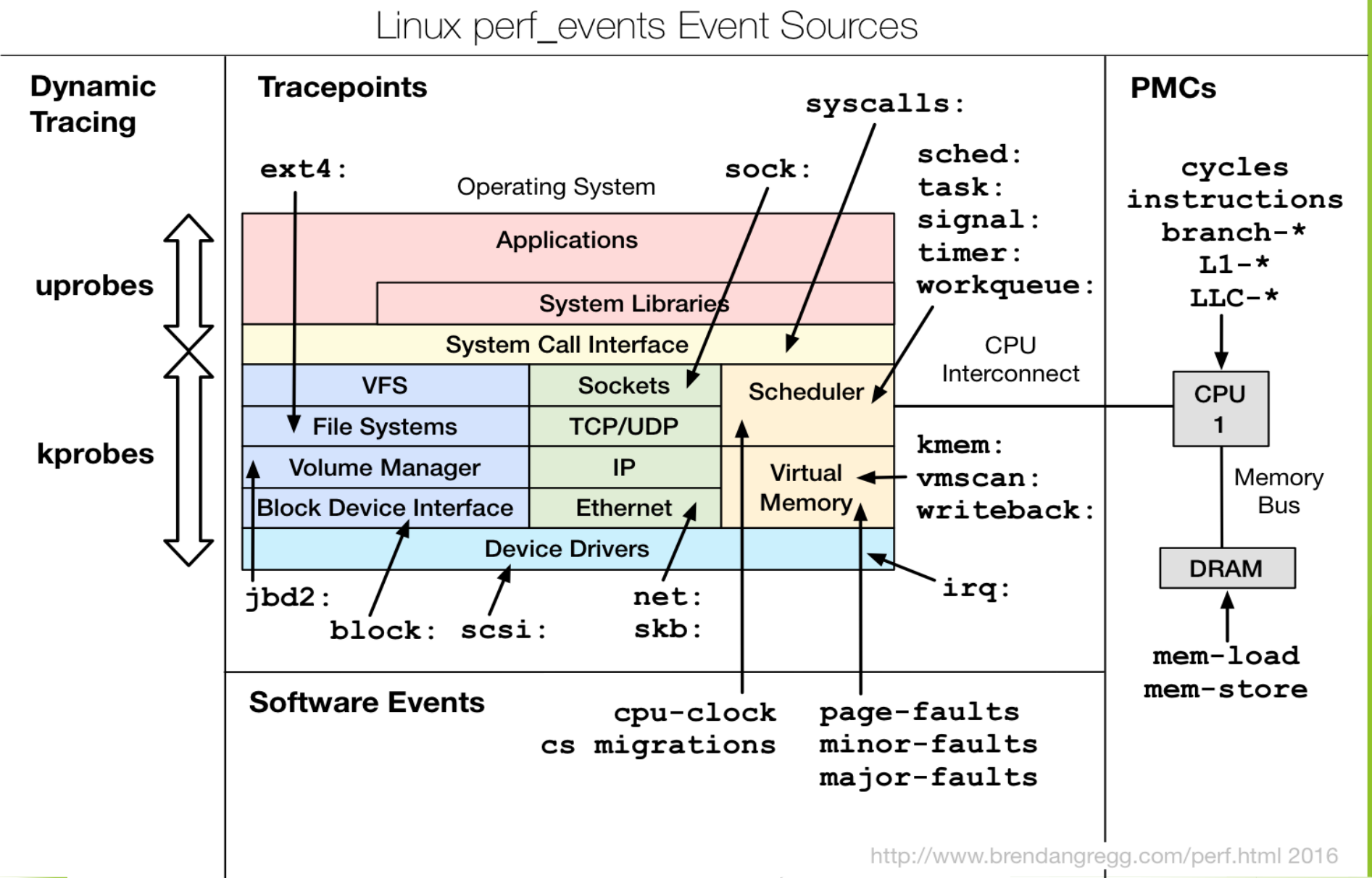
- Why is the kernel on-CPU so much? What code-paths?
- Which code-paths are causing CPU level 2 cache misses?
- Are the CPUs stalled on memory I/O?
- Which code-paths are allocating memory, and how much?
- What is triggering TCP retransmits?
- Is a certain kernel function being called, and how often?
- What reasons are threads leaving the CPU?

Perf

 # perf record -e block:block_rq_issue –ag

 # sudo perf report

Perf


Linux perf_events Event Sources
Dynamic Tracing
Tracepoints
PMCs
uprobes
kprobes
Operating System
Applications
System Libraries
System Call Interface
VFS
Sockets
File Systems
TCP/UDP
Volume Manager
IP
Block Device Interface
Ethernet
Device Drivers
Scheduler
Virtual Memory
CPU Interconnect
CPU 1
Memory Bus
DRAM
ext4:
jbd2:
block:
scsi:
sock:
net:
skb:
syscalls:
sched:
task:
signal:
timer:
workqueue:
kmem:
vmscan:
writeback:
irq:
cycles
instructions
branch-*
L1-*
LLC-*
mem-load
mem-store
Software Events
cpu-clock
cs
migrations
page-faults
minor-faults
major-faults

Perf

Perf Subcommands

Perf stat: collects and display event data (performance counters) during a command execution.

Perf record: run a command, store its profiling (sampling mode) in output file (perf.data) (no output is produced).

Perf report: display data previously recorded in output file (perf.data)

Perf

Perf diff: diff between perf.data files

Perf top: performance counter profile in realtime (live)

Perf probe: define dynamic trace points.

Perf

Listing all currently known events:

perf list

Listing sched tracepoints:

perf list 'sched:*'

Perf

 # perf probe –F *writepages*

BPF/BCC

BPF

BPF is a powerful component in the Linux kernel and the tools that make use of it are vastly varied and numerous.

BPF is the name, and no longer an acronym, but it was originally Berkeley Packet Filter and then eBPF for Extended BPF, and now just BPF. BPF is a kernel and user-space observability scheme for Linux.

A description is that BPF is a verified-to-be-safe, fast to switch-to, mechanism, for running code in Linux kernel space to react to events such as function calls, function returns, and trace points in kernel or user space.

BPF

To use BPF one runs a program that is translated to instructions that will be run in kernel space. Those instructions may be interpreted or translated to native instructions. For most users it doesn’t matter the exact nature.

While in the kernel, the BPF code can perform actions for events, like, create stack traces, count the events or collect counts into buckets for histograms.

Through this BPF programs provide both fast and immensely powerful and flexible means for deep observability of what is going on in the Linux kernel or in user space. Observability into user space from kernel space is possible, of course, because the kernel can control and observe code executing in user mode.

BPF

Running BPF programs amounts to having a user program make BPF system calls which are checked for appropriate privileges and verified to execute within limits. For example, in the Linux kernel version 5.4.44, the BPF system call checks for privilege with:

https://github.com/iovisor/bcc