USB and Linux

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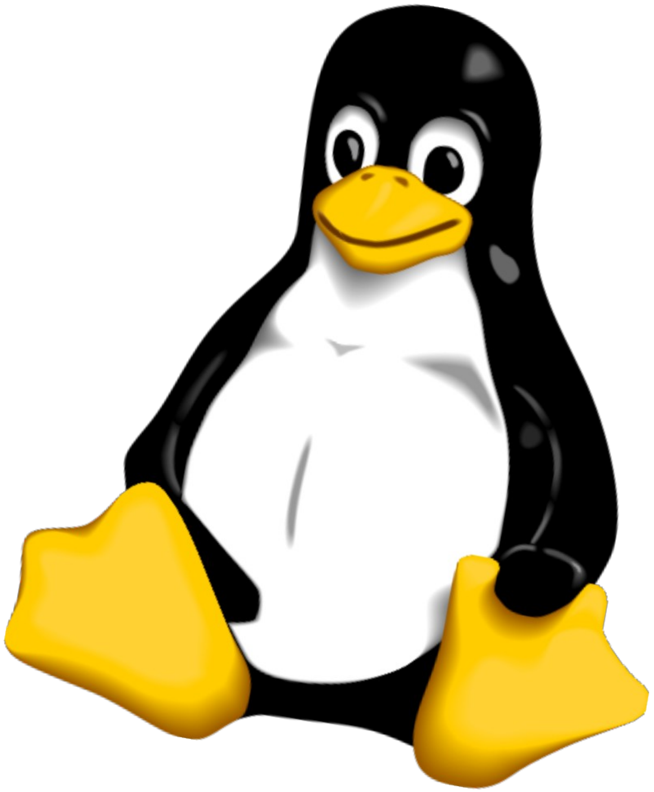

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SCaLE 16x

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About the Presenter

- Platform Software at **SoftIron**
  - Data center appliances (storage, transcoding)
  - Ceph-based storage appliances
  - OverDrive 3000/1000 ARM servers
- **OSS Development**
  - Linux Kernel
  - Firmware
  - Training
  - USB
    - **M-Stack** USB Device Stack for PIC
  - 802.15.4 wireless

USB Overview

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Universal Serial Bus

- Universal Serial Bus (USB)
- Standard for a high-speed, bi-directional, low-cost, dynamic bus.
- Created by the USB Implementers Forum (USB-IF)
  - USB-IF is a non-profit corporation formed by its member companies.
  - USB-IF develops and owns copyrights on the standards documents and logos.
    - http://www.usb.org

USB Bus Speeds

- **Low** Speed
  - 1.5 Mb/sec
- **Full** Speed
  - 12 Mb/sec
- **High** Speed
  - 480 Mb/sec
- **Super**Speed
  - 5.0 Gb/sec
- SuperSpeed+
  - 10Gb/sec

USB Bus Speeds

- Bus speeds are the **rate of bit transmission** on the bus
- Bus speeds are **NOT** data transfer speeds
- USB protocol can have **significant overhead**
- USB overhead **can be mitigated** if your protocol is designed correctly.

USB Standards

- USB **1.1** – 1998
  - Low Speed / Full Speed
- USB **2.0** – 2000
  - High Speed added
- USB **3.0** – 2008
  - SuperSpeed added
- USB Standards **do NOT imply** a bus speed!
  - *A **USB 2.0** device can be High Speed, Full Speed, or Low Speed*

Host and Device

- **Host**
  - Often a PC, server, or embedded Linux system
  - Responsible for **control** of the bus
  - Responsible for **initiating communication** with devices
  - Responsible for **enumeration** of attached devices.
  - One host per bus

Host and Device

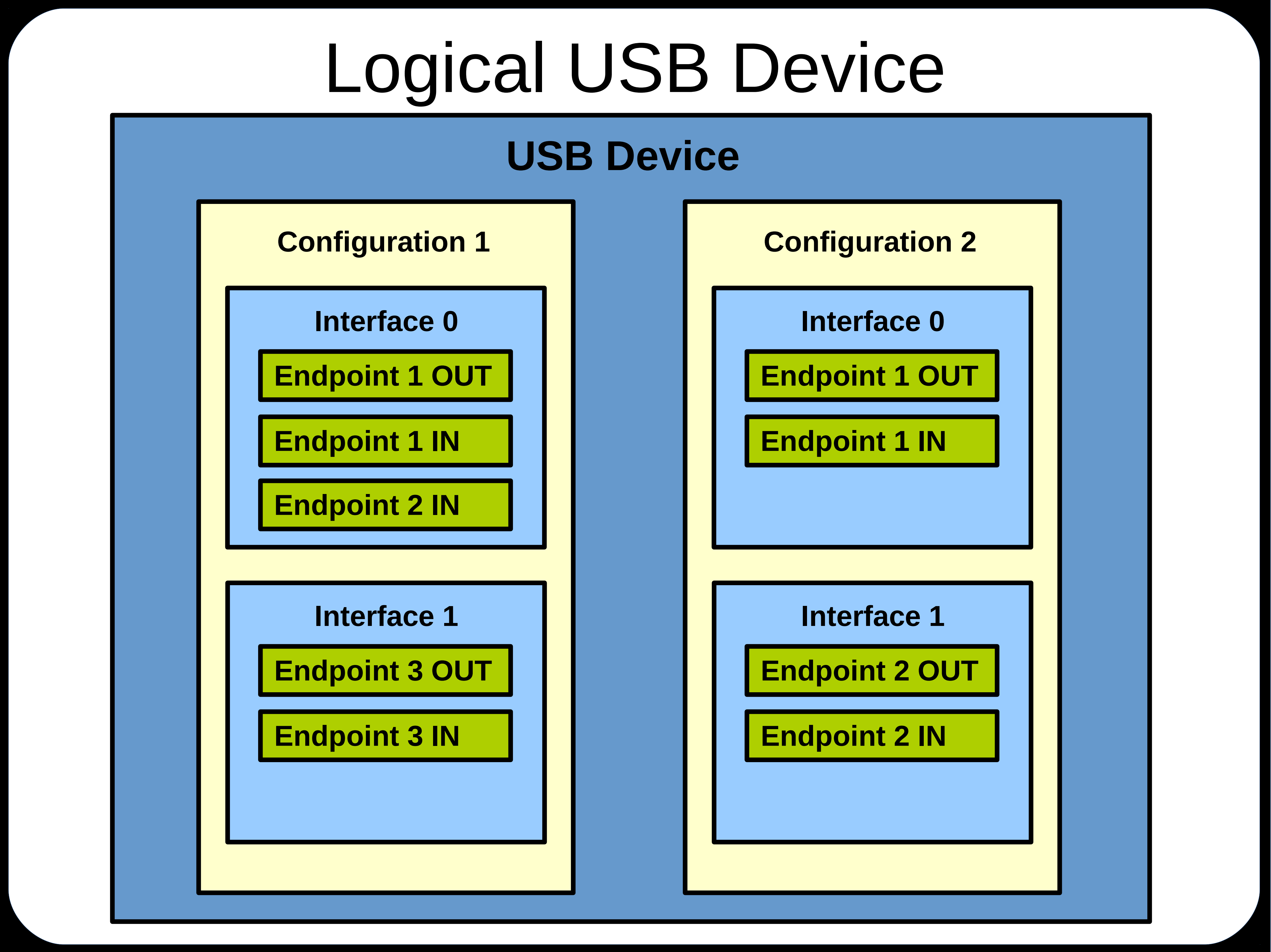
- **Device**
  - Provide functionality to the host
  - **Many devices** per bus
  - Can connect through **hubs**
    - Hubs are transparent to the device!
    - Hubs are transparent to host APIs
      - Hub drivers are built into the OS

The Bus

- USB is a **Host-controlled** bus
  - Nothing on the bus happens without the **host** first initiating it.
  - Devices cannot initiate a transaction.
  - The USB is a **Polled Bus**
  - The Host polls each device, requesting data or sending data.
  - Devices cannot interrupt the host!

Terminology

- In/Out
  - In USB parlance, the terms **In** and **Out** indicate direction from the **Host** perspective.
    - **Out**: Host to Device
    - **In**: Device to Host


Logical USB Device
USB Device
Configuration 1
Interface 0
Endpoint 1 OUT
Endpoint 1 IN
Endpoint 2 IN
Interface 1
Endpoint 3 OUT
Endpoint 3 IN
Configuration 2
Interface 0
Endpoint 1 OUT
Endpoint 1 IN
Interface 1
Endpoint 2 OUT
Endpoint 2 IN

USB Terminology

- **Device** – Logical or physical entity which performs a function.
  - Thumb drive, joystick, etc.
- **Configuration** – A mode in which to operate.
  - Many devices have one configuration.
  - Only one configuration is active at a time.

USB Terminology

- **Interface** – A related set of Endpoints which present a single feature or function to the host.
  - A configuration may have **multiple** interfaces
  - All interfaces in a configuration are **active at the same time**.
- **Endpoint** – A source or sink of data
  - Interfaces often contain **multiple endpoints**, each active all the time.

Logical USB Device

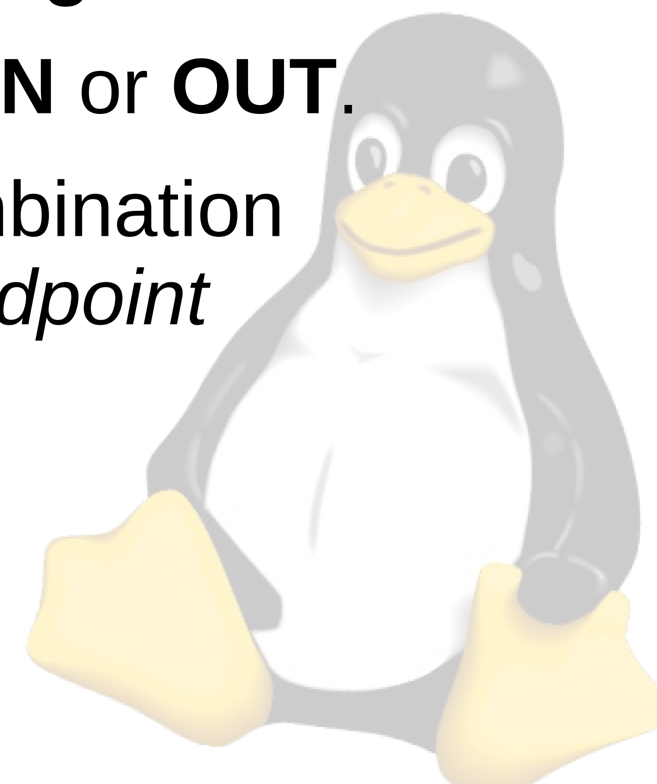
- Important to note:
  - A **device** can have multiple **configurations**.
    - Only one active at a time
  - A **configuration** can have multiple **interfaces**.
    - All active at the same time
  - An **interface** can have multiple **endpoints**.
    - All active at the same time

Logical USB Device

- Most USB devices only have one Configuration.
- Only **one configuration** can be active at a time.
- **All interfaces** within a configuration are active at the same time.
  - This is how **composite** devices are implemented.

Endpoint Terminology

- An **Endpoint Number** is a 4-bit integer associated with an endpoint (0-15).
- An endpoint transfers data in a **single direction**.
- An **Endpoint Direction** is either **IN** or **OUT**.
- An **Endpoint Address** is the combination of an *endpoint number* and an *endpoint direction*. Examples:
  - EP 1 IN
  - EP 1 OUT
  - EP 3 IN



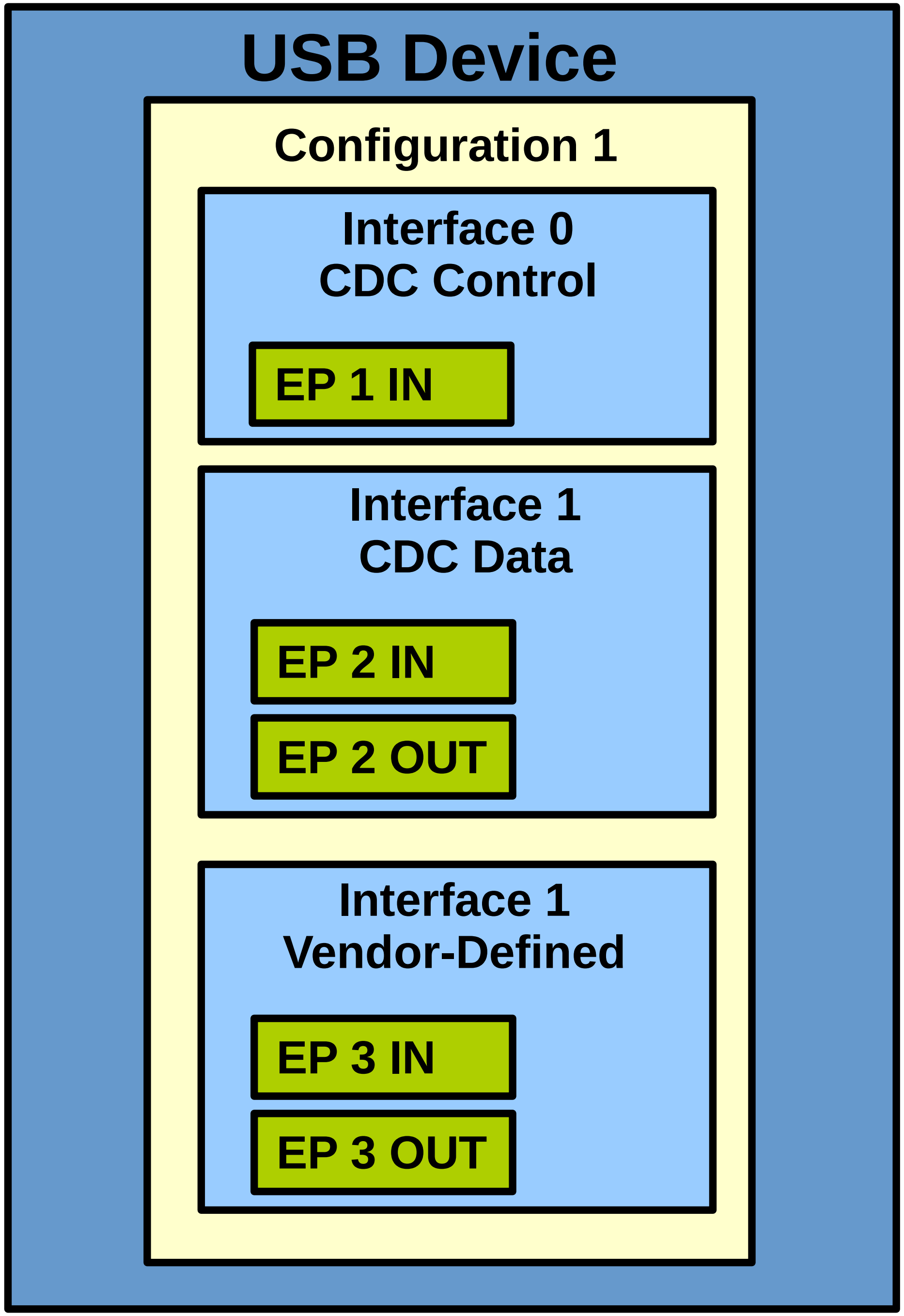
Endpoint Terminology

- Endpoint addresses are encoded with the direction and number in a **single byte**.
  - **Direction** is the MSb (1=IN, 0=OUT)
  - **Number** is the lower four bits.
  - Examples:
    - EP 1 IN = 0x81
    - EP 1 OUT = 0x01
    - EP 3 IN = 0x83
    - EP 3 OUT = 0x03
  - Tools like `lsusb` will show both

Endpoint Terminology

- Endpoint terminology is tricky (but important!)
  - A device can have up to **32 endpoints.**
    - IN and OUT endpoints for numbers 0-15.
- The same **Endpoint Number** is used to describe TWO endpoints.
  - EP 1 IN and EP 1 OUT are separate endpoints!
  - There is no such thing as a physical and logical endpoint.

Real-Life Example



- Composite Device:
  - Communication Device Class (CDC)
    - Often virtual **serial port**
    - **Two interfaces** are required for this class (control and data).
  - Vendor-Defined class
    - Can be used for generic data transfer

Descriptors

- USB is a **self-describing** bus
  - Each USB device contains all the information required for the host to be able to communicate with it (drivers aside)
    - No manual setting of baud rates, IRQ lines, base addresses, etc.
    - Plug devices in and they work
  - Devices communicate this data to the host using **descriptors.**

Descriptors

- The host will ask for a set of standard descriptors during **enumeration,** immediately upon a device being attached.
- The descriptors describe:
  - The device identifier (vendor/product IDs)
  - The logical structure of the device
    - Configurations, interfaces, endpoints
  - Which device classes are supported (if any)

Descriptors

- Typically, devices contain at least:
  - **Device** descriptor
  - **Configuration** descriptor
  - **Interface** descriptor
  - Class-specific descriptors
  - **Endpoint** descriptor
    - *Chapter 9 of the USB spec describes these standard descriptors*

Descriptors

- One tricky thing is that the host will request all descriptors which are part of a configuration as a single block.
  - This includes Configuration, Interface, class-specific, and endpoint descriptors
    - *The **Get Descriptor (Configuration)** request means all descriptors of a configuration*

Device Descriptor

```
const struct device_descriptor this_device_descriptor =
{
	sizeof(struct device_descriptor), // bLength
	DESC_DEVICE, // bDescriptorType
	0x0200, // USB Version: 0x0200 = USB 2.0, 0x0110 = USB 1.1
	0x00, // Device class (0 = defined at interface level)
	0x00, // Device Subclass
	0x00, // Protocol
	EP_0_LEN, // bMaxPacketSize0 (endpoint 0 in/out length)
	0xA0A0, // Vendor ID (Fake VID!! Don't use this one!)
	0x0001, // Product ID
	0x0001, // device release (BCD 1.0)
	1, // Manufacturer String Index
	2, // Product String Index
	0, // Serial Number String Index
	NUMBER_OF_CONFIGURATIONS // NumConfigurations
};
```

Configuration Descriptor

```
/*  The Configuration Packet, in this example, consists
 *  of four descriptor structs. Note that there is
 *  a single configurarion, a single interface, and two
 *  endpoints.
 */

struct configuration_1_packet {

        struct configuration_descriptor  config;

        struct interface_descriptor      interface;

        struct endpoint_descriptor       ep;

        struct endpoint_descriptor       ep1_out;

};
```

Configuration Descriptor (cont'd)

```
static const struct configuration_1_packet configuration_1 =
{
        {
        // Members from struct configuration_descriptor
        sizeof(struct configuration_descriptor),
        DESC_CONFIGURATION,
        sizeof(configuration_1), // wTotalLength (length of the whole packet)
        1, // bNumInterfaces
        1, // bConfigurationValue
        2, // iConfiguration (index of string descriptor)
        0X80, // bmAttributes
        100/2,   // 100/2 indicates 100mA
        },
```

Configuration Descriptor (cont'd)

```
{
// Members from struct interface_descriptor
sizeof(struct interface_descriptor), // bLength;
DESC_INTERFACE,
0x0, // InterfaceNumber
0x0, // AlternateSetting
0x2, // bNumEndpoints (num besides endpoint 0)
0xff, // bInterfaceClass: 0xFF=VendorDefined
0x00, // bInterfaceSubclass
0x00, // bInterfaceProtocol
0x02, // iInterface (index of string describing interface)
},
```

Configuration Descriptor (cont'd)

```
    {
    // Members of the Endpoint Descriptor (EP1 IN)
    sizeof(struct endpoint_descriptor),
    DESC_ENDPOINT,
    0x01 | 0x80, // endpoint #1 0x80=IN
    EP_BULK, // bmAttributes
    64, // wMaxPacketSize
    1,   // bInterval in ms.
    },
    {
    // Members of the Endpoint Descriptor (EP1 OUT)
    sizeof(struct endpoint_descriptor),
    DESC_ENDPOINT,
    0x01, // endpoint #1 OUT (msb clear => OUT)
    EP_BULK, // bmAttributes
    64, // wMaxPacketSize
    1,   // bInterval in ms.
    },
};
```

Configuration Descriptor

- Preceding configuration descriptor described:
  - One Configuration
  - One interface (vendor defined)
  - Two Bulk Endpoints
- See examples in `usb_descriptors.c` in any of the M-Stack examples.

Endpoints

- Four types of Endpoints
  - **Control**
    - **Bi-directional** pair of endpoints
    - **Multi-stage** transfers
      - Transfers acknowledged on the software level
        - Not just hardware!
      - Status stage can return success/failure
    - Used during **enumeration**
    - Can also be used for application
    - Mostly used for configuration items
    - Most robust type of endpoint

Endpoints

- **Interrupt**
  - Transfers a **small amount** of **low-latency** data
  - Reserves bandwidth on the bus
  - Used for **time-sensitive** data (HID).
- **Bulk**
  - Used for **large**, **time-insensitive** data (Network packets, Mass Storage, etc).
  - Does not reserve bandwidth on bus
    - Uses whatever time is left over

Endpoints

- **Isochronous**
  - Transfers a **large amount** of **time-sensitive** data
  - Delivery is **not guaranteed**
    - **No ACKs are sent**
  - Used for Audio and Video streams
    - Late data is as good as no data
    - Better to drop a frame than to delay and force a re-transmission

Endpoints

- **Reserved Bandwidth**
  - Different endpoint types will cause the bus to **reserve bandwidth** when devices are connected.
    - This is how **guaranteed, bounded latency** is implemented.
- **Interrupt**, **Isochronous**, and **Control** endpoints reserve bandwidth.
- **Bulk** gets whatever bandwidth is left unused each frame.

Endpoints

- **Endpoint Length**
  - The **maximum amount of data** an endpoint can support sending or receiving **per transaction**.
  - Max endpoint sizes:
    - Full-speed:
      - Bulk/Interrupt: **64**
      - Isoc: **1024**
    - High-Speed:
      - Bulk: **512**
      - Interrupt: **3072**
      - Isoc: **1024 x3**

Transactions

- Basic process of moving data to and from a device.
- USB is **host-controlled**. All transactions are initiated by the host.
  - Much like everything else in USB
- A single transaction on an endpoint can move bytes up to the **Endpoint Length**

Transactions

- Transactions have three **phases**
  - **Token** Phase
    - Host sends a token packet to the device
      - Indicates start of transaction
      - Indicates **type** of transaction (IN/OUT/SETUP)
  - **Data** Phase
    - Host or Device sends data
  - **Handshake** Phase
    - Device or host sends acknowledgement (ACK/NAK/Stall)

Transactions

- Transactions are handled on the **Hardware** level.
  - Strict timing is necessary
  - Software will **configure the hardware** to handle the transaction conditions before they occur.
    - This means the software/firmware must be prepared for what is coming!
    - not reacting to what has happened
  - Hardware will NAK if not configured

Transactions

- Endpoints are typically implemented in a hardware peripheral
  - Typically the USB hardware device is called the **Serial Interface Engine** (SIE)
  - SIE contains registers for each endpoint.
    - Pointer to data buffer (and length)
    - Firmware will configure these registers for transactions which are expected
  - SIE generates Interrupts when transactions complete

Transactions

- **Token** Phase
  - The host will initiate every transaction by sending a token. Tokens contain a **token type** and an **endpoint number**.
  - The device SIE will handle receipt of the **token** and will handle the **data** and **handshake** phases automatically.
    - This means the SIE endpoint will need to be configured ***before*** the token comes from the host.

Transactions

- For most cases, the token types are:
  - **IN**
    - The transaction will be an IN transaction, where the device sends data to the host using an IN endpoint.
    - Data phase will be **device-to-host** (ie: in)
    - Handshake phase (ack) will be **host-to-device**

Transactions

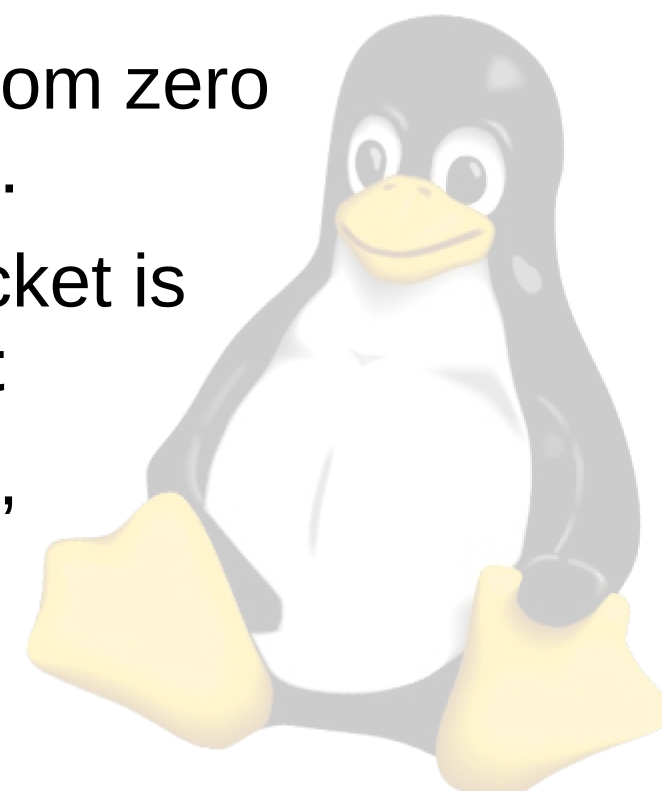
- Token types (cont'd):
  - **OUT**
    - The transaction will be an OUT transaction, where the host sends data to the device using an OUT endpoint.
    - Data phase will be **host-to-device** (ie: out)
    - Handshake phase (ack) will be **device-to-host.**

Transactions

- Token types (cont'd):
  - **SETUP**
    - The transaction will be a SETUP transaction
      - SETUP transactions are used to start a **Control Transfer** on a Control endpoint pair.
        - Usually endpoint 0
      - Setup transactions indicate there will be more transactions following, and what types they will be.
    - A Setup transaction is like an OUT transaction, but the data phase always contains a SETUP packet.

Transactions

- **Data** Phase
  - The data phase contains the data which is to be transferred.
  - The data phase packet can be from zero bytes up to the **endpoint length**.
  - For **IN** transactions, the data packet is sent from the **device** to the **host**
  - For **OUT** or **SETUP** transactions, the data packet is sent from the **host** to the **device**.



Transactions

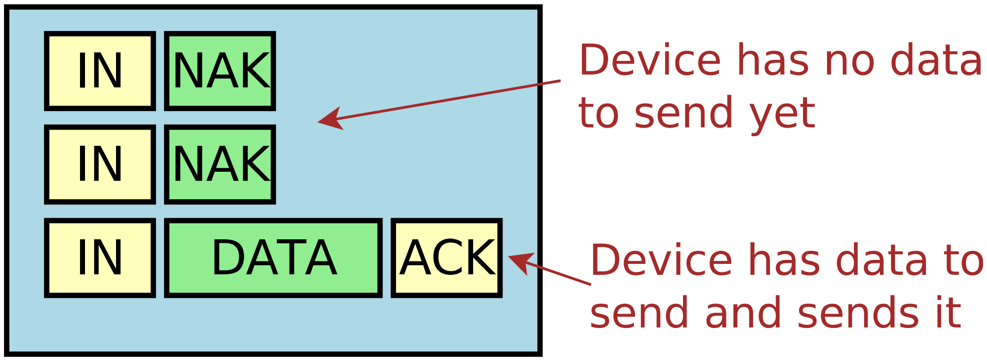
- **Data** Phase (cont'd)
  - If there is no data to be sent (IN transaction), or if the device is unable to receive (OUT transaction), the device can skip the data stage and send a **NAK**.
    - This ends the transaction prematurely.
  - A NAK tells the host to **try again later**.
    - It is **not a failure** of any kind.
    - NAKs are a normal part of the flow regulation of USB.
      - *The Host is often faster than the device!*

Transactions

- **Handshake** Phase
  - ACK, NAK, or STALL
  - Opposite in direction from the data phase
  - Indicates **hardware** reception of data
  - ACK – Reception OK
  - NAK
    - Unable to receive, try again
  - STALL
    - Protocol error

Transaction

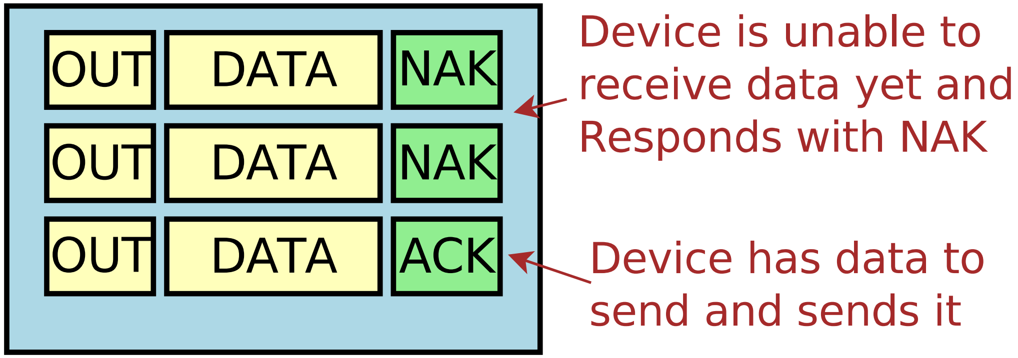
- **IN** Transaction



- The device can NAK as long as it's not ready to send data.
- The Host will retry (up to a timeout) as long as the device NAKs.

Transaction

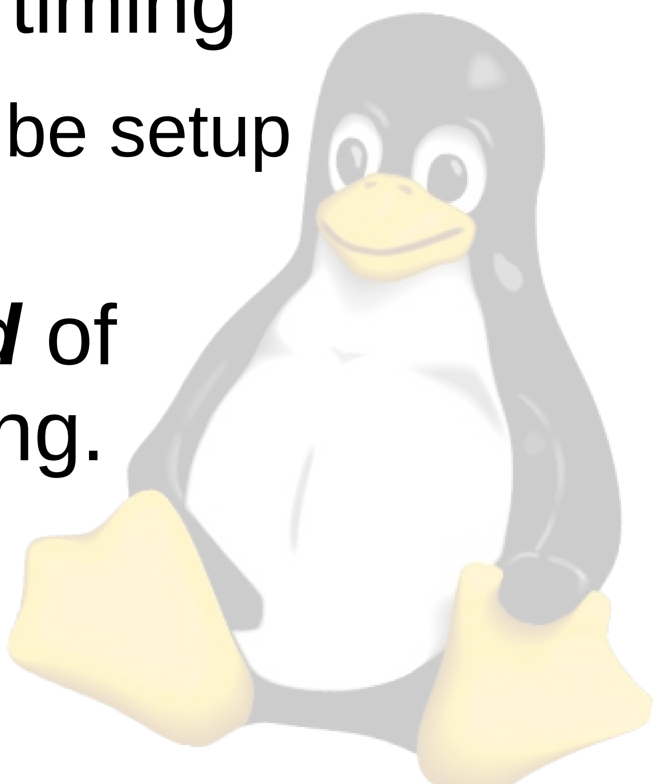
- **OUT** Transaction



- The device can NAK as long as it's not ready to **receive** data.
- The Host will retry (up to a timeout) as long as the device NAKs.

Transactions

- The timing between the phases is very tight
  - Too tight for software/firmware
- The hardware SIE handles this timing
  - The hardware endpoint needs to be setup ***before*** the IN token arrives.
- This means you must be ***ahead*** of the host, in a manner of speaking.



Transactions

- For **IN** transactions (**device-to-host**)
  - Device firmware will put data to send in the hardware SIE buffer
  - Host will (sometime later) send the IN token
  - Device SIE will send the data (data stage)
    - Device SIE will resend until ACK is received
  - Host will send an ACK to the device
    - *Note that the data will not get sent until the **host initiates** the transaction by sending the IN token to the device*

Transactions

- For **OUT** transactions (**host-to-device**)
  - Device firmware configures a hardware SIE buffer to **receive** data
  - Host will (sometime later) send the OUT token
  - Host will send the data.
  - Device SIE will send an ACK
  - Device SIE will interrupt the MCU/CPU.

Transactions

- Note that for OUT transactions, the data is sent **before** the device can respond with a NAK.
  - This is inefficient, as the host will send the entire data phase for each retry.
- USB 2.0 introduced the **PING** token for high-speed devices.
  - After an OUT-NAK, the host can send PING tokens to the device.
  - The device will ACK when it is ready to receive data.

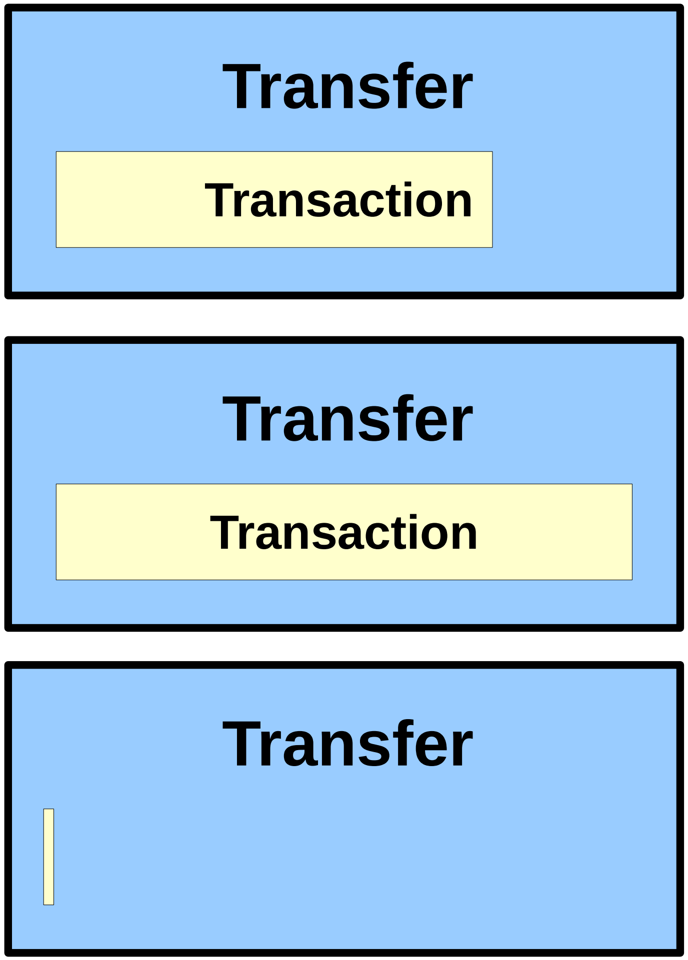
Transactions

- PING packets are sent as long as the device NAKs them.
  - Once the device responds with an ACK, a normal OUT transaction is sent.
- Typically PING is handled by the SIE hardware.
  - It is part of the timing-critical part of a USB transaction.
  - This is automatic and transparent to device drivers running on the host.

Transactions and Transfers

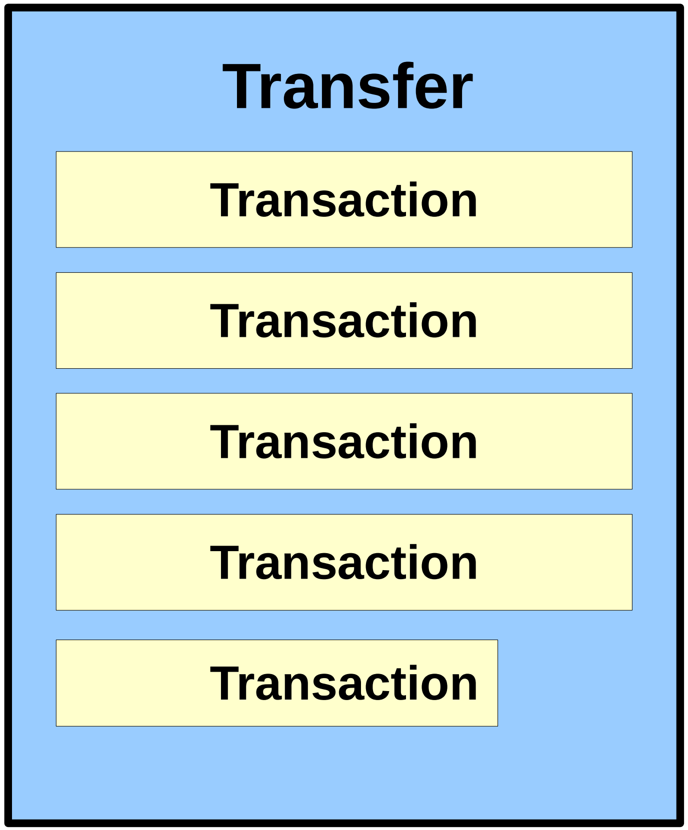
- **Transaction**
  - Delivery of service to an endpoint
  - Max data size: **Endpoint length**
- **Transfer**
  - **One or more** transactions moving information between host and device.
  - ➢ *Transfers can be large, even on small endpoints!*

Small Transfers



- The simplest transfer contains a **single transaction**.
- A transaction's size can be any length from zero bytes up to the **endpoint length.**

Large Transfers



- Transfers can contain **more than one transaction.**
- Transfers are ended by:
  - A **short transaction** OR
  - When the **desired amount of data** has been transferred
    - *As requested by the host*

Large Transfers

- Transfers are ended when:
  - A **short transaction** happens
  - The requested amount of data has been transfered
- A **short transaction** is one which is smaller than the endpoint length.
  - This means in a multi-transaction transfer, all transactions except the last must be the endpoint length

Large Transfers

- Sometimes a host **does not know** the number of bytes it is asking for.
  - For example a string descriptor.
- The host will ask for the **maximum** number of bytes it can accept and will rely on the **device** to end the transfer early.
- This gives an interesting **edge case**

Large Transfers

- There are four cases of large transfers. Let's consider **IN** transfers:
  - Case 1:
    - Host asks for a number of bytes which is **not a multiple** of the endpoint length.
    - device returns this many bytes.
  - Case 2:
    - Host asks for a **multiple** of the endpoint length.
    - device returns this many bytes.

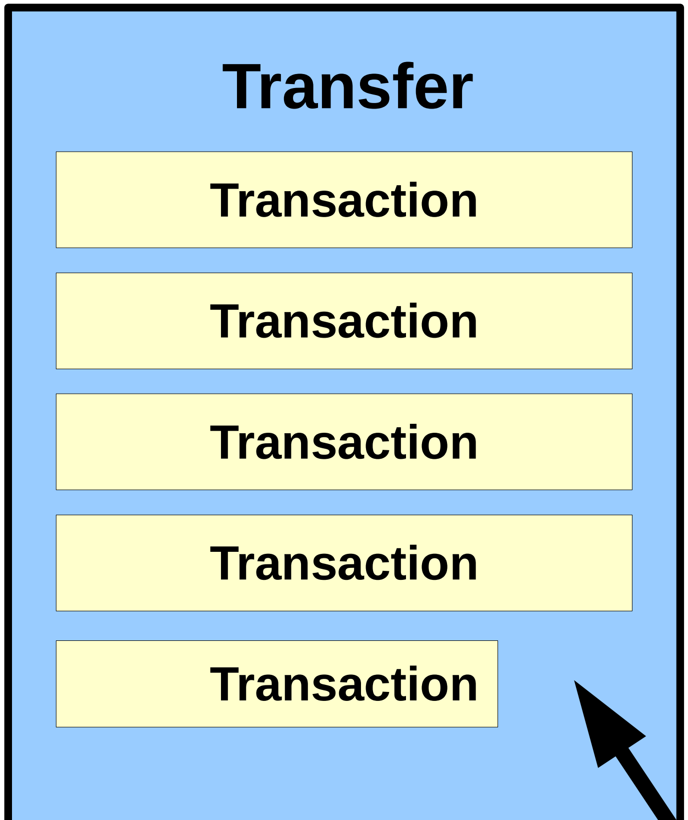
Large Transfers

- Four cases (cont'd):
  - Case 3:
    - Host asks for a number of bytes
    - device returns **fewer than requested,** which is **not a multiple** of the endpoint length.
  - Case 4:
    - Host asks for a number of bytes
    - device returns **fewer than requested,** but it **is a multiple** of the endpoint length

Large Transfers

- In cases #1, #2, and #3, the device can simply return the number of bytes it intends to return.

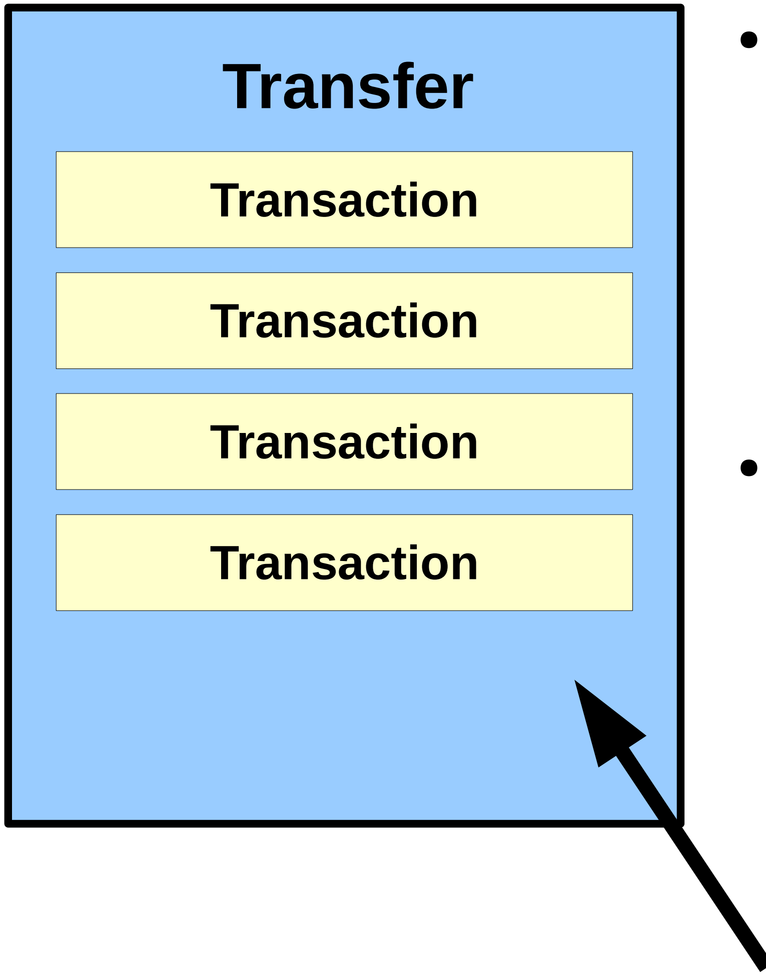
Large Transfers – Case 1



- Case 1:
  - Host asks for a number of bytes which is **not a multiple** of the endpoint length.
  - Device Returns this many bytes.
- Transfer is ended by:
  - A **short transaction** AND
  - The **desired amount of data** has been transferred

- 16-byte endpoint length
- Requested 76 bytes
- 4x 16-byte transactions
- 1x 12-byte transaction

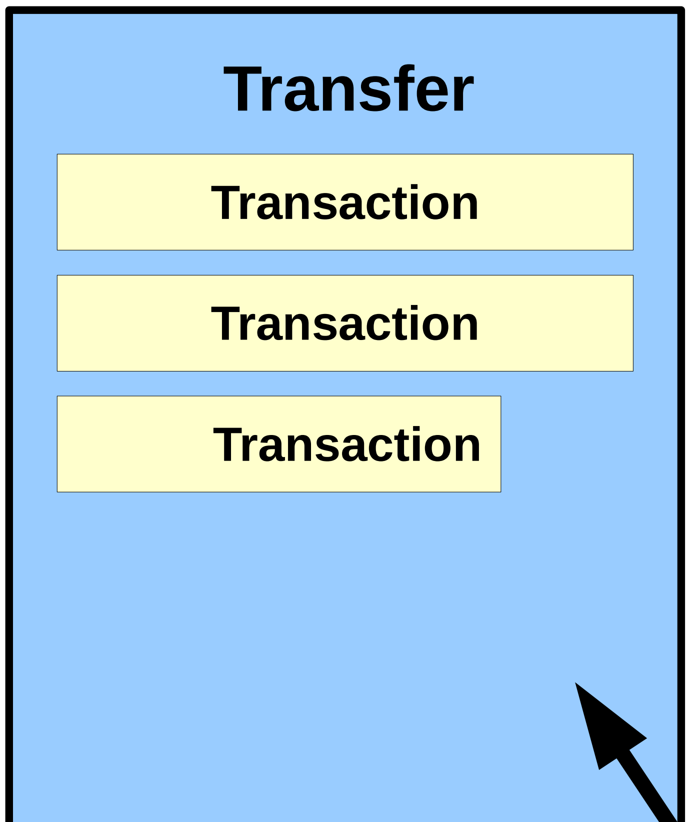
Large Transfers – Case 2



- Case 2:
  - Host asks for a number of bytes which **is a multiple** of the endpoint length.
  - Device Returns this many bytes.
- Transfer is ended by:
  - The **requested amount of data** has been transferred

- 16-byte endpoint length
- Requested 64 bytes
- 4x 16-byte transactions

Large Transfers – Case 3



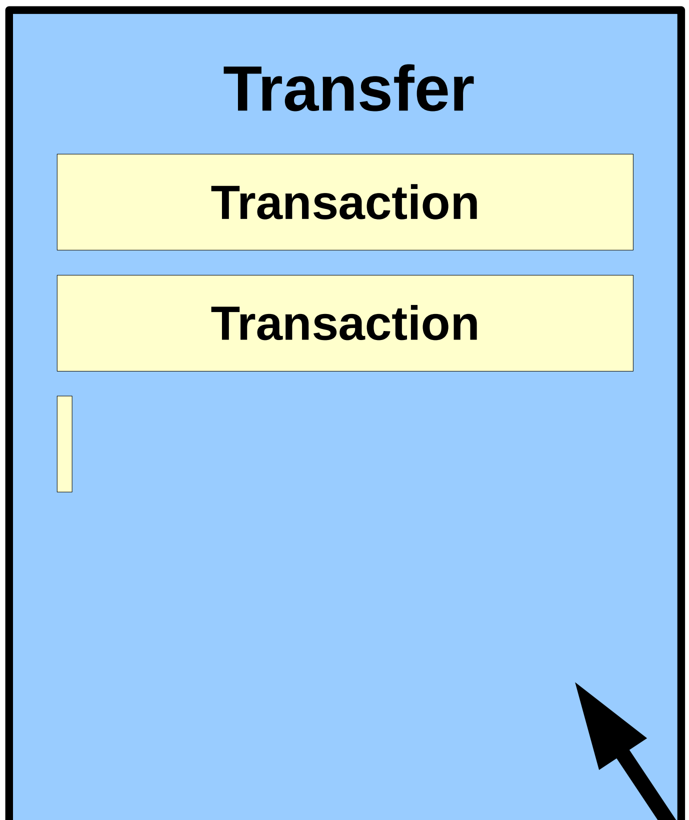
- Case 3:
  - Host asks for a number of bytes.
  - Device returns **fewer than requested,** which is **not a multiple** of the endpoint length.
- Transfer is ended by:
  - A **short transaction**

- 16-byte endpoint length
- Requested 255 bytes
- Device returns 44 bytes
- 2x 16-byte transactions
- 1x 12-byte transaction

Large Transfers

- Case #4 is an edge case
  - Host requested a number of bytes
  - Device returns fewer than requested, which **is a multiple** of the endpoint length.
- Since the number of bytes being returned **is a multiple** of the endpoint length, the transfer will not naturally end with a short transaction.
- Device must add a **zero-length packet!**

Large Transfers – Case 4



- Case 4:
  - Host asks for a number of bytes.
  - Device returns **fewer than requested,** which **is a multiple** of the endpoint length.
- Transfer is ended by:
  - A **short transaction,** in this case a **zero-length packet**

- 16-byte endpoint length
- Requested 255 bytes
- Device returns 32 bytes
- 2x 16-byte transactions
- 1x 0-byte transaction

Control Transfers

- The transfers discussed so far have been **Bulk** or **Interrupt** transfers.
- **Control transfers** are different and more complicated.
  - Control transfers have additional structure and are bi-directional.
  - Consist of multiple **stages**
    - Each stage is one or more transactions
  - Information is sent both ways (IN and OUT)

Control Transfers

- Control transfers begin with the **SETUP** stage.
  - A SETUP transaction is like an OUT transaction except that the data stage is an 8-byte SETUP packet.
    - The SETUP packet has information on:
      - The logical **recipient** of the transfer
      - The **direction** of the transfer
      - The **number of bytes** which will be sent or requested
      - The **identifier** or **type** of the request

Control Transfers

- Chapter 9 of the USB specification defines **standard requests** which are used during enumeration of a device.
  - Set Address
  - Get Descriptor
  - Get Configuration
  - Set Configuration

  others...

Control Transfers

- Device classes also define their own requests:
  - **CDC** (*Communication Device Class*)
    - Set Line Coding
    - Set Control Line State
    - Send Break
  - **HID** (*Human Interface Device*)
    - Get Report Descriptor
    - Get Report
    - Set Report

Control Transfers

- Next is the **data** stage
  - The data stage is one or more IN or OUT transactions which contain the data.
  - The same rules apply about multi-transaction transfers, lengths and the zero-length packet.
  - The direction and desired data length are in the SETUP packet (part of the setup stage).

Control Transfers

- Next is the **status** stage
  - The status stage is a single, zero-length IN or OUT transaction
    - Opposite in direction from the data stage
  - It serves as an acknowledgement
    - Not just of receipt, but of validity
    - It’s acknowledgment from the software layer that the data in the data stage has been processed correctly.
  - On error, the endpoint should **STALL**

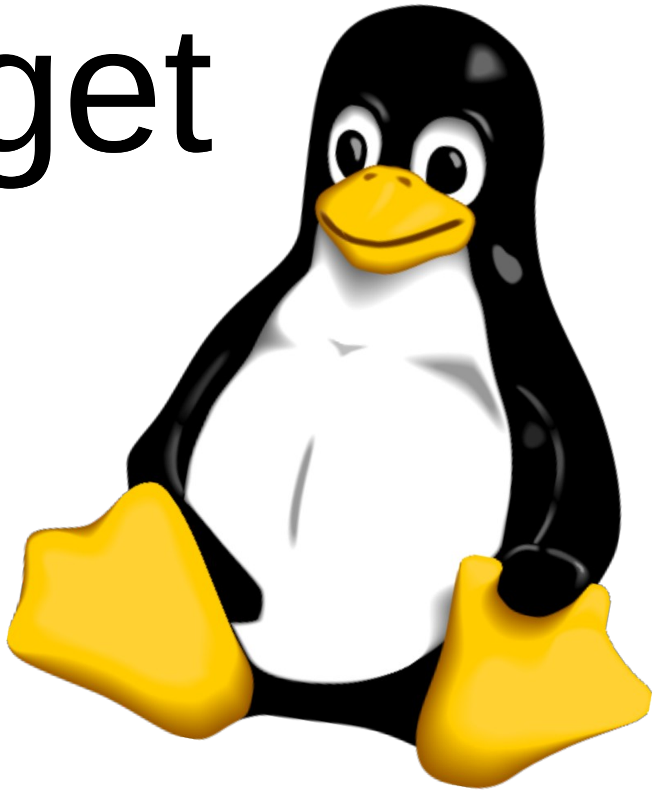
Control Transfers

- Additional Token:
  - **STALL**
    - Used to indicate failure or rejection of data
    - Used in **control** transfers
    - Sometimes used on other endpoints
      - Mass Storage uses it on bulk endpoints
    - Sending a STALL token on any endpoint marks that endpoint as stalled.
    - Stalls must be cleared by the host
      - Automatically cleared with a SETUP for control endpoints.

Control Transfers

- The terminology gets confusing:
- **Transactions**
  - The lowest level of communication
  - Handled by hardware
  - Three **phases** (token, data, handshake)
- **Control Transfers**
  - Three **stages** (setup, data, status)

Linux USB Gadget



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USB Gadget Subsystem

- In addition to providing the USB **host** subsystem you are familiar with, Linux also provides a **device** subsystem, called **gadget**.
  - Gadget is a Linux-specific name.
- The gadget subsystem provides a framework for creating USB devices using a Linux system.
  - …if the hardware supports it. Most embedded USB controllers do.

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USB Gadget Subsystem

- USB gadget subsystem provides:
  - Framework
  - USB **Device Controller** (UDC) drivers
    - Hardware drivers
  - USB **device class** implementations
    - Software drivers (so to speak)
  - Configuration through **configfs**
    - Pseudo-filesystem for configuring certain kernel services

Configfs

- Configfs is a pseudo-filesystem used to manage kernel objects.
  - Pseudo-filesystems contain files which are not present on any disk.
  - The files are backed by objects in the running kernel.
    - Creating, deleting, or changing files and directories will immediately have an effect in the kernel
      - Kernel callback functions are called

Configfs

- Configfs (cont'd)
  - Data integrity is enforced by mechanism.
    - Only valid file / directory names will be allowed to be created
    - Invalid values will not be allowed to be written to files
    - System calls (read/write/mkdir,etc) will simply fail if invalid names or values are used.
    - ➢ *This is far better than silent failure*

USB Gadget

- To configure your USB Gadget:
  - Mount configfs (if not already done)
  - Create a directory for the gadget
  - Set the vid/pid/strings
  - Create a directory for the **configuration**
  - Create a directory for the **function**
    - Mass storage, HID, CDC/ACM, etc.
  - **Link** the function to the configuration
  - Enable the gadget

Simple Example – ACM Device

```
#!/bin/sh -ex

modprobe libcomposite

# Mount configfs locally
mkdir -p config
mount none config -t configfs

# Create the USB gadget configuration
mkdir -p config/usb_gadget/
cd config/usb_gadget/

# Create a gadget called g1
mkdir g1
cd g1

# Set the VID/PID/Strings
echo 0x1a0a >idVendor
echo 0xbadd >idProduct
mkdir strings/0x409
```

Simple Example – ACM Device

```
# Set the VID/PID/Strings (cont'd)
echo 12345 >strings/0x409/serialnumber
echo "Signal 11" >strings/0x409/manufacturer
echo "Test" >strings/0x409/product

# Create a configuration called c.1
mkdir configs/c.1
mkdir configs/c.1/strings/0x409
echo "Config1" >configs/c.1/strings/0x409/configuration

# Create a function (tty CDC/ACM) named usb0
mkdir functions/acm.usb0

# Link that function to configuration c.1
ln -s functions/acm.usb0 configs/c.1

# Enable the USB device. Find the device
# name in /sys/class/udc/ .
echo musb-hdrc.0 >UDC
```

Simple Example - Device

- The above example will create a CDC/ACM device.
  - A Linux host will identify this device as `/dev/ttyACM`*n*.
  - The device/gadget side will create a device node at `/dev/ttyGS0`.
    - Read and write to/from this node from the gadget to communicate with the host.

Simple Example – ACM Device

- Lab #1
  - On the device:
    - Run the script from the previous slides
  - On the host, run:
    - `dmesg`
      - Check for the new device name
    - `sudo screen /dev/ttyACM`*n*
  - On the device, run:
    - `echo “some text” >/dev/ttyGS0`
    - `cat /dev/ttyGS0`

Simple Example – ACM Device

- In theory, the device can be disabled, changed, and re-enabled.
- In practice, on many parts, this is fraught with oopses, hangups, and other peril.
- Generally, you will want to setup your gadget and leave it.

Simple Example – ACM Device

- The previous example is designed to be as simple as possible
  - No source code, even!
- CDC/ACM is the best solution for emulating a serial port, and that's all.
- Don't use CDC/ACM as an arbitrary solution for connectivity
  - It's inefficient
  - Its burdensome on the end user

USB Gadget

- We showed ACM, but what other protocols are implemented?
  - Start in Kernel source at: `Documentation/filesystems/gadget_configfs.txt`
  - Which references: `Documentation/ABI/testing`
  - Where you can: `ls *usb-gadget*`

USB Gadget

As of 4.15, these gadgets are documented:

```
configfs-usb-gadget
configfs-usb-gadget-acm
configfs-usb-gadget-ecm
configfs-usb-gadget-eem
configfs-usb-gadget-ffs
configfs-usb-gadget-hid
configfs-usb-gadget-loopback
configfs-usb-gadget-mass-storage
configfs-usb-gadget-midi
configfs-usb-gadget-ncm
configfs-usb-gadget-obex
configfs-usb-gadget-phonet
configfs-usb-gadget-printer
configfs-usb-gadget-rndis
configfs-usb-gadget-serial
configfs-usb-gadget-sourcesink
configfs-usb-gadget-subset
configfs-usb-gadget-tcm
configfs-usb-gadget-uac1
configfs-usb-gadget-uac2
configfs-usb-gadget-uvc
```

See these files in: `Documentation/ABI/testing/`

USB Gadget

- Briefly, some supported functions are:
  - acm – CDC/ACM virtual serial port
  - ecm/eem/ncm/phonet/rndis/subset – Virtual network device
  - ffs – function filesystem
    - Define a custom class from userspace
  - hid – Human interface device
  - loopback – for testing
  - mass-storage – present drives to the host

USB Gadget

- Supported functions (cont'd):
  - midi – musical instrument
  - printer – printers
  - serial – serial interface on the gadget side, but bulk interface on the host side
  - sourcesink – source and sink for testing
  - tcm – USB-attached SCSI
  - uac1/2 – USB audio class, v1 and v2
  - uvc - video

USB Gadget

- Find more information about each gadget in it's respective source file:

  ```
  drivers/usb/gadget/function/f_*.c
  ```

- As usual in the kernel, documentation is hit-or-miss

FunctionFS

- The gadget subsystem provides a function called FunctionFS, which allows complete configuration of the device through a user space application.
- The user space application provides:
  - All the descriptors/strings
- Functionfs will then use the descriptors to create **device nodes** for each endpoint.

FunctionFS

- The user space application can then read and write to/from these device nodes to move data across the bus.
- This is better than using ACM because there is no TTY layer in the way.
  - The TTY layer will chop up your write()s
  - Using FFS, one write() is one USB transfer.
    - This can get you close to wire speed

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FunctionFS

- Modifying the previous script which (which creates an ACM device), use the ffs function instead of the acm function.
- After this, mount the FunctionFS pseudo-filesystem for your device.
  - This filesystem will give you an ep0 pseudo-file.
  - Writing to this ep0 file with descriptors will configure your device

FunctionFS

- Start your user space program which will write to the ep0 file and configure the gadget.
  - Based on your configuration (the descriptors) FunctionFS will then create a pseudo-file for each endpoint.
- Enable the USB device
- Read/write the endpoint pseudo-files to transfer data.

FunctionFS Example

```
# Setup the function, FunctionFS (named usb0)
mkdir functions/ffs.usb0
ln -s functions/ffs.usb0 configs/c.1

# Mount the function filesystem for usb0
cd ../../../
mkdir -p ffs
mount usb0 ffs -t functionfs

# From inside the mounted ffs directory, run your
# user space program and wait until it's started.
cd ffs
../ffs-test/ffs-test & # from the Linux kernel
sleep 3
cd ..

# Enable the USB device
echo musb-hdrc.0 >config/usb_gadget/g1/UDC
```

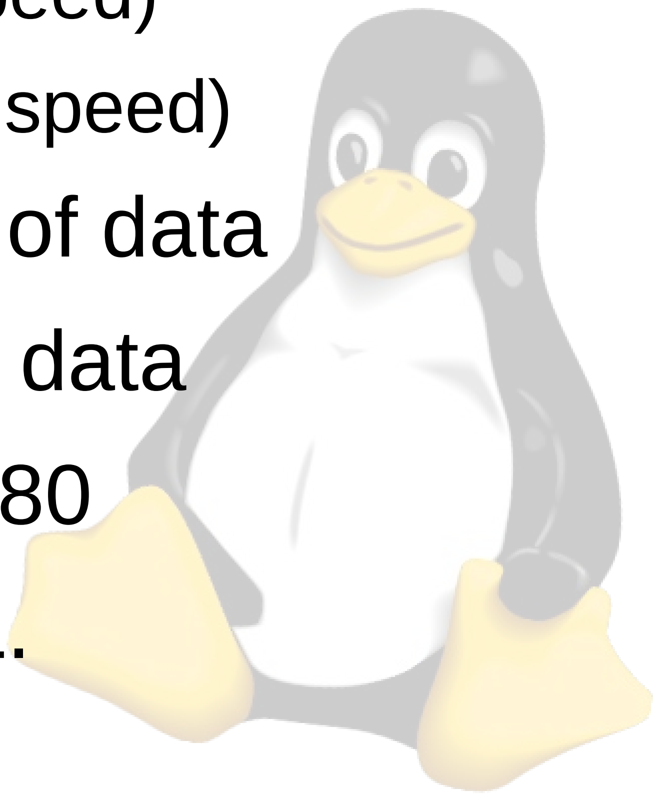
FunctionFS Example

- The kernel provides a sample user space program for FunctionFS.
- Unfortunately, it's more of a test program than an example to learn from.
  - Few comments
  - Complex design and indirection
  - Ambiguous naming
- Find it in:

  `tools/usb/ffs-test.c`

FunctionFS Example

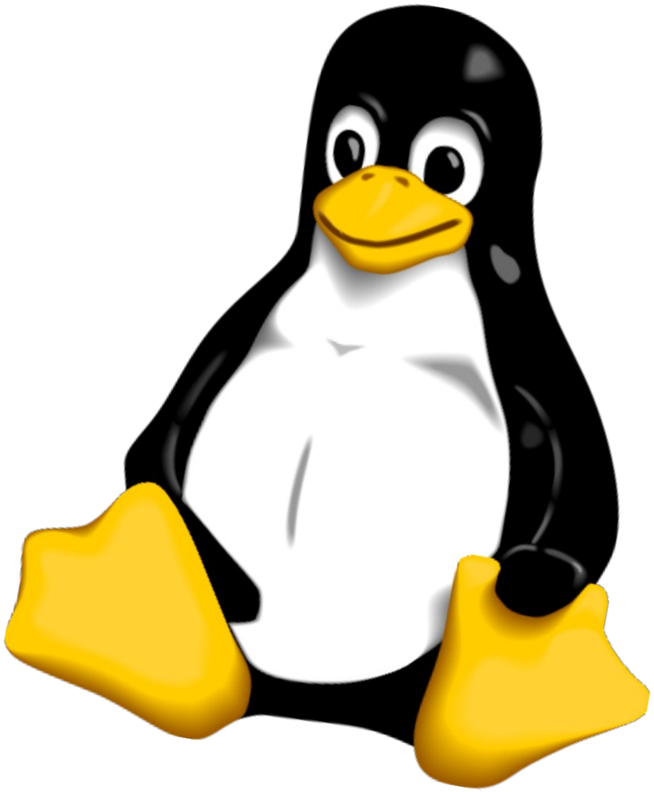
- The kernel sample creates:
  - ep0 (unused for this example)
  - ep1 – Bulk IN, 512 bytes (high speed)
  - ep2 – Bulk OUT, 512 bytes (high speed)
- ep1 creates an endless source of data
- ep2 sinks an endless stream of data
- ep1/2 are address 0x81 and 0x80
- Also note that it's explicitly GPL.



FunctionFS Lab

- Lab #2
  - Modify the gadget script for functionFS
  - Build the `ffs-test` program from the kernel
  - Copy it to the target's home directory
  - Run the gadget script.
  - Use `lsusb` and `dmesg` to observe the device is detected on the host.

libusb



libusb

- libusb is a multi-platform host-side USB library
  - Linux, BSD, OS X, Windows, others
- Runs in user space. No kernel programming required.
- Easy to use synchronous API
- High-performance asynchronous API
- Supports all versions of USB

libusb

- A libusb host runs on a general purpose multi-process OS.
  - Sufficient permissions are required to open a device
  - Opening a device or interface may be exclusive (only one process at a time).

libusb

- From a host perspective, the basic unit of a USB connection is the USB **interface**, not the **device.**
  - This is because devices can have **multiple interfaces**, each of which may require a **different** driver.
  - Some composite devices may have some **standard** interfaces (eg: CDC) and also some **vendor-defined** interfaces (eg: earlier example)

libusb Example

```
int main(int argc, char **argv)
{
        libusb_device_handle *handle;
        unsigned char buf[64];
        int length = 64, actual_length, i, res;

        /* Init libusb */
        if (libusb_init(NULL))
                return -1;

        /* Open the device. This is a shortcut function. */
        handle = libusb_open_device_with_vid_pid(
                                        NULL, 0xa0a0, 0x0001);
        if (!handle) {
                perror("libusb_open failed: ");
                return 1;
        }

        /* Claim the interface for this process */
        res = libusb_claim_interface(handle, 0);
        if (res < 0) {
                perror("claim interface");
                return 1;
        }
```

libusb Example (cont'd)

```
        /* Initialize the data */
        my_init_data_function(buf, length);

        /* Send some data to the device */
        res = libusb_bulk_transfer(
                   handle, 0x01, buf, length, &actual_length, 5000);
        if (res < 0) {
                fprintf(stderr, "bulk transfer (out): %s\n",
                                                  libusb_error_name(res));
                return 1;
        }

        /* Receive data from the device */
        res = libusb_bulk_transfer(handle, 0x81, buf, length,
                                                       &actual_length, 5000);
        if (res < 0) {
                fprintf(stderr, "bulk transfer (in): %s\n",
                                                     libusb_error_name(res));
                return 1;
        }

        /* Process the data */
        my_process_received_data_function(buf, &actual_length);

        return 0;
}
```

libusb

- Observations:
  - `libusb`, and `libusb_bulk_transfer()` deal with **transfers**, not transactions.
    - The length can be **arbitrarily long** and longer than the endpoint length.
    - If so, libusb will behave as expected, initiating transactions until the required amount of data has been transferred.
    - If the device returns a short packet, the transfer will end, and **`actual_length`** will indicate the actual amount of data received.

libusb

- Observations (cont'd):
  - The `libusb_bulk_transfer()` function is used for both IN and OUT transfers
    - The endpoint address (which contains the direction) is used to determine whether it's an IN or OUT transfer.

libusb

- Observations (cont'd):
  - The interface must be **claimed** before it can be used.
    - If another process, or a kernel driver, is using this interface, it will kick the other driver off.
    - This can be good or bad depending on your point of view.

libusb

- Observations (cont'd):
  - The libusb functions take a **timeout** parameter.
    - This timeout is how long the device has to complete the transfer.
    - It can be any value the host desires
      - The host is in charge of the bus!
    - 5 seconds is good for general purposes, but the author recently made one over 90 seconds!
      - It all depends on the use case!

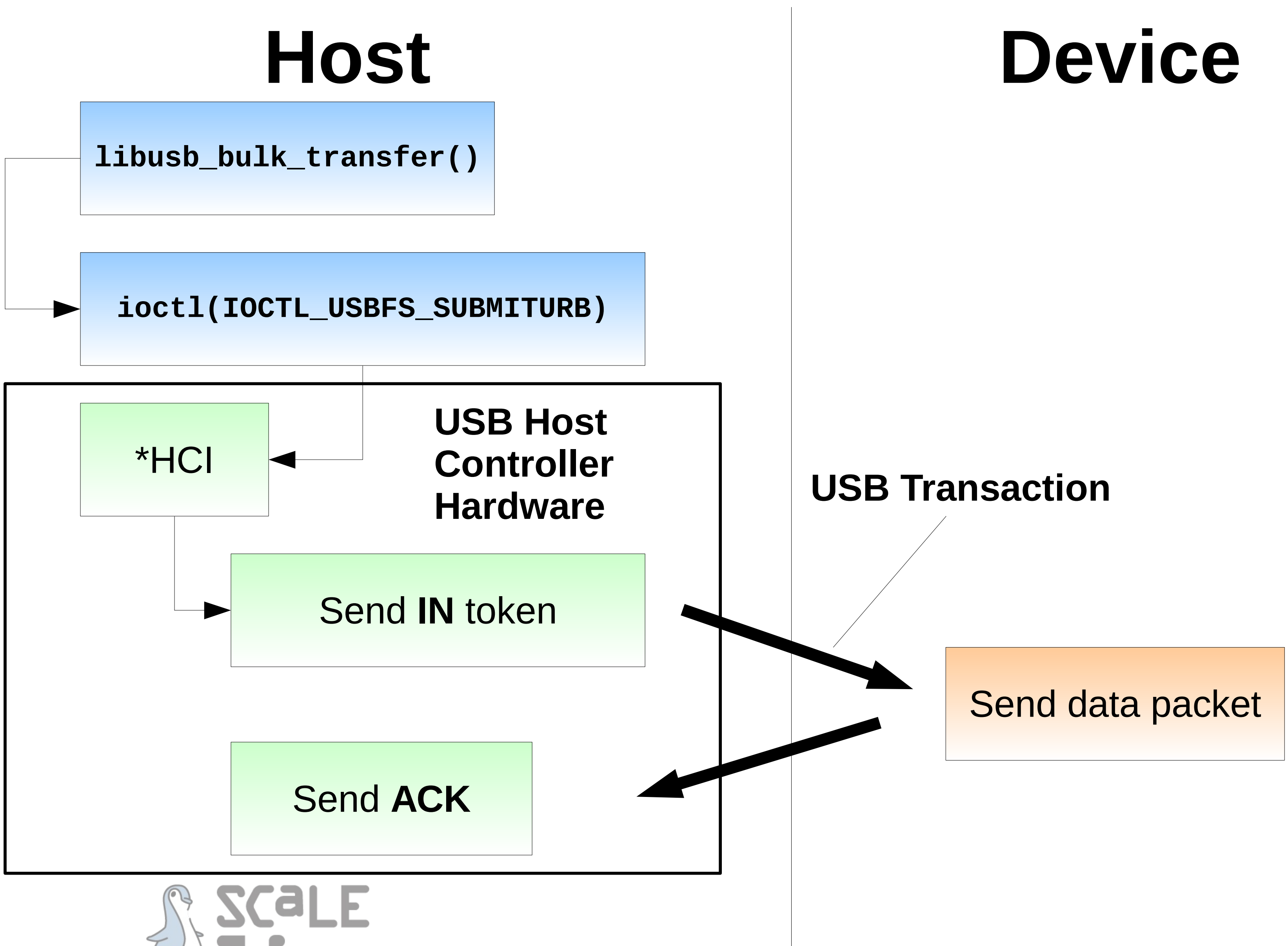
libusb

- The simple example used libusb's **synchronous API**.
  - Good for **infrequent**, **single** transfers.
    - Easy to use, blocking, return code
  - Bad for any kind of **performance-critical** applications.
    - Why? Remember the nature of the USB bus....

Synchronous API Issues

- The USB Bus
  - Entirely host controlled
  - Device only sends data when the host controller specifically **asks** for it.
  - The host controller will only ask for data when a **transfer is active**.
    - libusb **creates a transfer** when (in our example) `libusb_bulk_transfer()` is called.

Synchronous API Issues



Synchronous API Issues

- USB Bus
  - After one transfer completes, nothing happens on the bus until the next libusb transfer function is called.
  - One might think it's good enough to call `libusb_bulk_transfer()` in a **tight loop**.
    - Tight loops are **not tight enough**!
      - For short transfers, time spent in software will be more than time spent in hardware!
      - All time spent in software is time a **transfer is not active**!

Asynchronous API

- Fortunately libusb and the kernel provide an **asynchronous API**.
  - Create **multiple** transfer objects
  - **Submit** transfer objects to the kernel
  - Receive a **callback** when transfers complete
- When a transfer completes, there is another (submitted) transfer already queued.
  - **No downtime** between transfers!

Asynchronous API Example

```
static struct libusb_transfer
*create_transfer(libusb_device_handle *handle, size_t length) {
        struct libusb_transfer *transfer;
        unsigned char *buf;

        /* Set up the transfer object. */
        buf = malloc(length);
        transfer = libusb_alloc_transfer(0);
        libusb_fill_bulk_transfer(transfer,
                handle,
                0x81 /*ep*/,
                buf,
                length,
                read_callback,
                NULL/*cb data*/,
                5000/*timeout*/);

        return transfer;
}
```

Asynchronous API Example (cont'd)

```c
static void read_callback(struct libusb_transfer *transfer)
{
        int res;

        if (transfer->status == LIBUSB_TRANSFER_COMPLETED) {
                /* Success! Handle data received */
        }
        else {
                printf("Error: %d\n", transfer->status);
        }

        /* Re-submit the transfer object. */
        res = libusb_submit_transfer(transfer);
        if (res != 0) {
                printf("submitting. error code: %d\n", res);
        }
}
```

Asynchronous API Example (cont'd)

```
/* Create Transfers */
for (i = 0; i < 32; i++) {
        struct libusb_transfer *transfer =
                create_transfer(handle, buflen);
        libusb_submit_transfer(transfer);
}

/* Handle Events */
while (1) {
        res = libusb_handle_events(usb_context);
        if (res < 0) {
                printf("handle_events()error # %d\n",
                       res);

                /* Break out of this loop only on fatal error.*/
                if (res != LIBUSB_ERROR_BUSY &&
                    res != LIBUSB_ERROR_TIMEOUT &&
                    res != LIBUSB_ERROR_OVERFLOW &&
                    res != LIBUSB_ERROR_INTERRUPTED) {
                        break;
                }
        }
}
```

Asynchronous API

- This example creates and queues **32 transfers**.
- When a transfer completes, the completed transfer object is **re-queued**.
- All the transfers in the queue can conceivably complete **without a trip to user space**.

Asynchronous API

- For All types of Endpoint:
  - The Host **will not send** any IN or OUT tokens on the bus unless a **transfer object is active**.
  - The bus is **idle** otherwise
  - Create and submit transfer objects using the functions on the preceding slides.

Performance

- For more information on USB performance, see my ELC 2014 presentation titled ***USB and the Real World***
  - http://www.signal11.us/oss/elc2014/
  - *Several devices and methods compared*

API Summary

- All traffic is initiated by the **Host**
- In user space, this is done from **libusb**:
  - Synchronous:

```
libusb_control_transfer()
libusb_bulk_transfer()
libusb_interrupt_transfer()
```

  - Asynchronous:

```
libusb_create_transfer()
libusb_submit_transfer()
```

Libusb Lab

- Lab #3
  - Create a user space application to talk to the FunctionFS gadget device you created earlier
  - Remember:
    - Find the VID/PID from the script
    - ep81 is bulk IN, ep01 is bulk OUT

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