Basics of I²C on Linux

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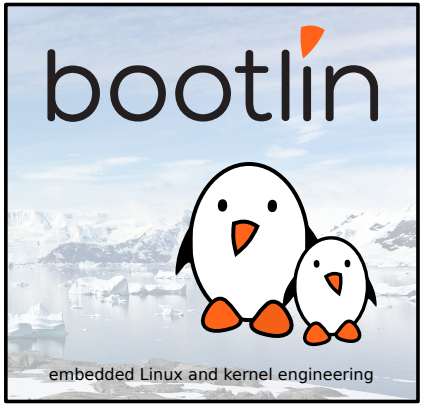

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- Embedded Linux engineer at **Bootlin**
  - Embedded Linux experts
  - Engineering services: Linux BSP development, kernel porting and drivers, Yocto/Buildroot integration, real-time, boot-time, security, multimedia
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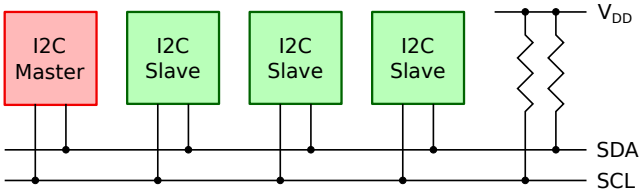
What is I²C

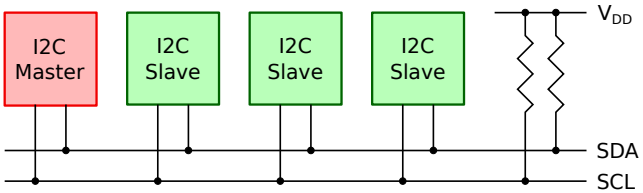
What is I²C



https://docs.kernel.org/i2c/summary.html

- A bus for Inter-Integrated-Circuit communication
- Design for hardware simplicity: 2 wires, many chips per bus, flexible
- Not discoverable, not plug-and-play
- Low speed: 100-400 kHz (with 1 MHz and 3.4 MHz extensions)
- Also known as: I2C, IIC, TWI, TWSI, ...
- https://en.wikipedia.org/wiki/I²C
- https://docs.kernel.org/i2c/

Roles



https://docs.kernel.org/i2c/summary.html

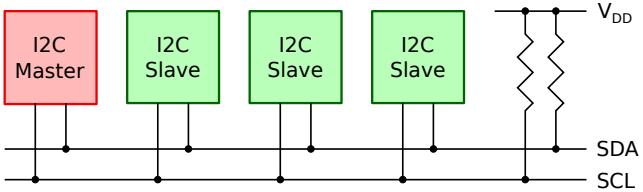
Adapter

- Other names: Master, Controller, bus
- Initiates all transactions
- Usually one (multimaster possible)
- Has no address

Client

- Other names: Slave, Device
- Responds to transactions
- Many per bus
- 7-bit address set in hardware (10-bit extension)

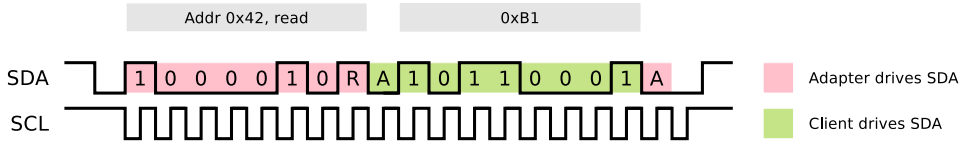
Two wires



https://docs.kernel.org/i2c/summary.html

- Two wires
  - SDA: data, bidirectional
  - SCL: “clock”
    - Not really a clock
    - SDA moved at SCL falling edge, SDA read at SCL rising edge
    - Mostly driven by adapter, sometimes also by clients (clock stretching)
- Open collector

Communication protocol



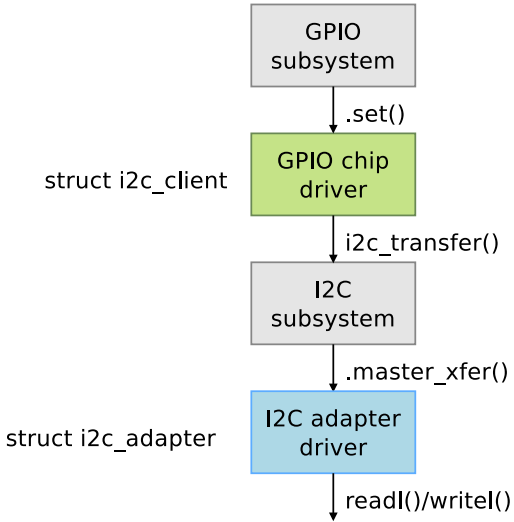
1. Start condition
2. Adapter sends: client address (7 bit) + direction bit (R/W)
3. Client sends ACK
4. Client sends one byte
5. Adapter sends ACK
6. Stop condition

The SMBus protocol

- Designed for chip communication on PC motherboards
- Mostly a subset of I²C
- Defines several commands
  - Register write: S addr+W A reg A data P
  - Register read: S addr+W A reg A RS addr+R A data NA P
- Often I²C and SMBus clients can be mixed on the same bus
  - Linux recommends using SMBus APIs for I²C chips when possible
- https://en.wikipedia.org/wiki/System_Management_Bus

I²C in the Linux Driver Model

The I2C subsystem in the linux kernel



Sysfs view

I2C “Devices” includes both adapters and clients:

```
# ls -l /sys/bus/i2c/devices/
lrwxrwxrwx ... 0-0039 -> ../../../devices/platform/soc/40012000.i2c/i2c-0/0-0039
lrwxrwxrwx ... 0-004a -> ../../../devices/platform/soc/40012000.i2c/i2c-0/0-004a
lrwxrwxrwx ... 1-0052 -> ../../../devices/platform/soc/40015000.i2c/i2c-1/1-0052
lrwxrwxrwx ... 2-0028 -> ../../../devices/platform/soc/5c002000.i2c/i2c-2/2-0028
lrwxrwxrwx ... 2-0033 -> ../../../devices/platform/soc/5c002000.i2c/i2c-2/2-0033
lrwxrwxrwx ... i2c-0 -> ../../../devices/platform/soc/40012000.i2c/i2c-0
lrwxrwxrwx ... i2c-1 -> ../../../devices/platform/soc/40015000.i2c/i2c-1
lrwxrwxrwx ... i2c-2 -> ../../../devices/platform/soc/5c002000.i2c/i2c-2
lrwxrwxrwx ... i2c-3 -> ../../../devices/platform/soc/40012000.i2c/i2c-0/i2c-3
```

Device Tree

Device tree example

arch/arm/boot/dts/stm32mp15xx-dkx.dtsi

```
&i2c4 {
    i2c-scl-rising-time-ns = <185>;
    i2c-scl-falling-time-ns = <20>;
    clock-frequency = <400000>;
    status = "okay";
    // ...

    stusb1600@28 {
        compatible = "st,stusb1600";
        reg = <0x28>;
        interrupts = <11 IRQ_TYPE_LEVEL_LOW>;
        interrupt-parent = <&gpioi>;
        pinctrl-names = "default";
        pinctrl-0 = <&stusb1600_pins_a>;
        status = "okay";
        // ...
    };

    pmic: stpmic@33 {
        compatible = "st,stpmic1";
        reg = <0x33>;
        // ...
    }
}
```

More properties

- Adapter node
  - `compatible`
  - `#address-cells = <1>` (1 address number per client chip)
  - `#size-cells = <0>` (no size numbers per client chip)
  - Optional: `clock-frequency` (frequency of bus clock in Hz)
  - Optional: `i2c-scl-falling-time-ns`, `i2c-sda-falling-time-ns`, ...
  - Optional: `scl-gpios`, `sda-gpios`: for GPIO bus recovery
  - Optional: `single-master` or `multi-master`
  - Adapter-specific properties
  - ...
  - One subnode per client chip
    - `reg = <`*client address*`>` (Look for "Slave address" on the datasheet)
    - `compatible`
    - Client-specific properties
- See Documentation/devicetree/bindings/i2c/i2c.txt

Writing *client* device drivers

Client device driver: declare the driver

drivers/gpio/gpio-pca9570.c

```
static struct i2c_driver pca9570_driver = {
    .driver = {
        .name = "pca9570",
        .of_match_table = pca9570_of_match_table, // --> see later
    },
    .id_table = pca9570_id_table, // --> see later
    .probe_new = pca9570_probe, // --> see later
};
module_i2c_driver(pca9570_driver);
```

Client device driver: i2c and device tree tables

drivers/gpio/gpio-pca9570.c

```
static const struct i2c_device_id pca9570_id_table[] = {
    { "pca9570", 4 },
    { "pca9571", 8 },
    { /* sentinel */ }
};
MODULE_DEVICE_TABLE(i2c, pca9570_id_table);

static const struct of_device_id pca9570_of_match_table[] = {
    { .compatible = "nxp,pca9570", .data = (void *)4 },
    { .compatible = "nxp,pca9571", .data = (void *)8 },
    { /* sentinel */ }
};
MODULE_DEVICE_TABLE(of, pca9570_of_match_table);
```

Client device driver: probe function

drivers/gpio/gpio-pca9570.c

```
static int pca9570_probe(struct i2c_client *client)
{
    struct pca9570 *gpio;

    gpio = devm_kzalloc(&client->dev, sizeof(*gpio), GFP_KERNEL);
    if (!gpio)
        return -ENOMEM;

    gpio->chip.get = pca9570_get; // --> see later
    gpio->chip.set = pca9570_set; // --> see later
    // ...

    i2c_set_clientdata(client, gpio);

    return devm_gpiochip_add_data(&client->dev, &gpio->chip, gpio);
}
```

Client device driver: recap

drivers/gpio/gpio-pca9570.c

```
static int pca9570_probe(struct i2c_client *client)
{
    // 1. allocate driver-specific struct
    // 2. fill it
    // 3. device-specific initializations
    // 4. i2c_set_clientdata(client, <driver-specific struct>)
    // 5. register to appropriate subsystem (GPIO, RTC, input, IIO, ...)
}

// 6. Describe i2c device in struct i2c table and device tree table
// 7. Describe driver in a struct i2c_driver
// 8. module_i2c_driver(): declare the driver
```

Client device driver: requesting I²C transactions

drivers/gpio/gpio-pca9570.c (simplified)

```
static void pca9570_set(struct gpio_chip *chip, unsigned offset, int value)
{
    struct pca9570 *gpio = gpiochip_get_data(chip);
    struct i2c_client *client = to_i2c_client(gpio->chip.parent);
    u8 buffer;

    buffer = /* chip-specific code */;

    i2c_smbus_write_byte(client, buffer);
}
```

Requesting I²C transactions

- Simple buffer transfer
  - `i2c_smbus_write_byte()`: send one byte
  - `i2c_smbus_read_byte()`: receive one byte
  - `i2c_master_send()`: send multiple bytes
  - `i2c_master_recv()`: receive multiple bytes
- Register-like access
  - `i2c_smbus_write_byte_data()`: write a register
  - `i2c_smbus_read_byte_data()`: read a register
  - Plus variants transferring words or buffers
- And more, see:
  - https://docs.kernel.org/i2c/i2c-protocol.html
  - https://docs.kernel.org/i2c/smbus-protocol.html
- ...or use `i2c_transfer()`, the "swiss army knife of Linux I2C"
  - Makes any number of transfers
  - Does repeated start by default
  - Various flags to tweak its behaviour

i2c_transfer()

sound/soc/codecs/adau1701.c (simplified)

```
static int adau1701_reg_read(void *context, unsigned int reg, unsigned int *value)
{
    uint8_t send_buf[2], recv_buf[3];
    struct i2c_msg msgs[2];

    msgs[0].addr = client->addr;
    msgs[0].len = sizeof(send_buf);
    msgs[0].buf = send_buf; // pre-filled
    msgs[0].flags = 0; // Write transaction by default

    msgs[1].addr = client->addr;
    msgs[1].len = size;
    msgs[1].buf = recv_buf;
    msgs[1].flags = I2C_M_RD; // Read transaction

    ret = i2c_transfer(client->adapter, msgs, ARRAY_SIZE(msgs));
    if (ret < 0)                        return ret;
    else if (ret != ARRAY_SIZE(msgs))   return -EIO;
}
```

Userspace tools

I2C from userspace

- The first rule about I2C from userspace:
- Do not use I2C from userspace
- Use the RTC/ALSA/IIO device instead, I2C is just to get you there

i2c-tools

- The `i2c-tools` package provides tools to access I²C on the command line
- Useful for debugging, testing, some simple prototyping
- Accesses the I²C bus via `/dev/i2c-0`, `/dev/i2c-1`...
- Assume devices have registers, SMBus-like
- `WARNING! This program can confuse your I2C bus, cause data loss and worse!`
- https://i2c.wiki.kernel.org/index.php/I2C_Tools

- `i2cdetect`: detect devices on a bus
- No guarantee it works (I²C is not discoverable by the spec)

```
# i2cdetect -l
i2c-0   i2c   STM32F7 I2C(0x40012000)    I2C adapter
i2c-1   i2c   STM32F7 I2C(0x40015000)    I2C adapter
i2c-2   i2c   STM32F7 I2C(0x5c002000)    I2C adapter
i2c-3   i2c   i2c-0-mux (chan_id 0)      I2C adapter
# i2cdetect -y 2
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f
00:                         -- -- -- -- -- -- -- --
10: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
20: -- -- -- -- -- -- -- -- 28 -- -- -- -- -- -- --
30: -- -- -- UU -- -- -- -- -- -- -- -- -- -- -- --
40: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
50: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
60: -- -- -- -- -- -- -- -- -- -- -- -- -- -- -- --
70: -- -- -- -- -- -- -- --
#
```

-- No response
28 Response from address 28
UU Address in use (by driver)

i2cget and i2cset

- i2cget: read a register value
- i2cset: set a register value
- Can use various types of SMBus and I²C transactions
- Limited to 8-bit register address

```
# i2cget -y 2 0x28 0x1b
0x21
# i2cset -y 2 0x28 0x55
#
```

i2cdump

- `i2cdump`: dump value of all registers

```
# i2cdump -y 2 0x28
No size specified (using byte-data access)
     0  1  2  3  4  5  6  7  8  9  a  b  c  d  e  f    0123456789abcdef
00: 00 00 00 00 00 00 12 00 11 20 00 00 f3 00 00 00    ......?.? ..?...
10: 04 00 00 40 00 00 00 00 20 00 00 21 00 e0 00 00    ?..@.... ..!.?..
20: a0 32 00 00 00 ac 00 00 02 00 00 00 00 00 01 10    ?2...?..?.....??
30: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
40: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
50: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
60: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
70: a3 2c 91 01 08 2c d1 02 00 2c c1 03 00 f0 b0 04    ?,???,??.,??.???
80: 00 af 40 06 00 00 90 01 08 2c d1 02 00 2c c1 03    .?@?..???,??.,??
90: 00 00 00 00 00 00 40 00 00 00 00 00 00 00 00 00    ......@.........
a0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
b0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
c0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
d0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
e0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
f0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00    ................
#
```

i2ctransfer

- `i2ctransfer`: the “swiss army knife of Linux I2C”, in userspace
- Example: reimplement the `i2cget -y 2 0x28 0x1b` command:

```
# i2ctransfer -y 2 w1@0x28 0x1b r1@0x28
0x21
#
```

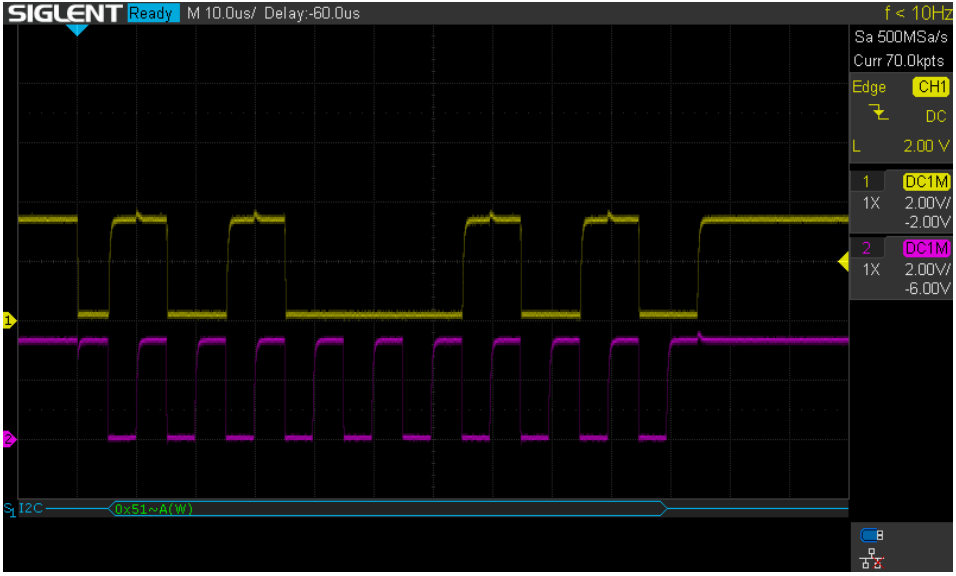
- `w1@0x28` Write transaction, 1 byte, client address 0x28
- `0x1b` Data to send in the write transaction
- `r1@0x28` Read transaction, 1 byte, client address 0x28

Hardware tools

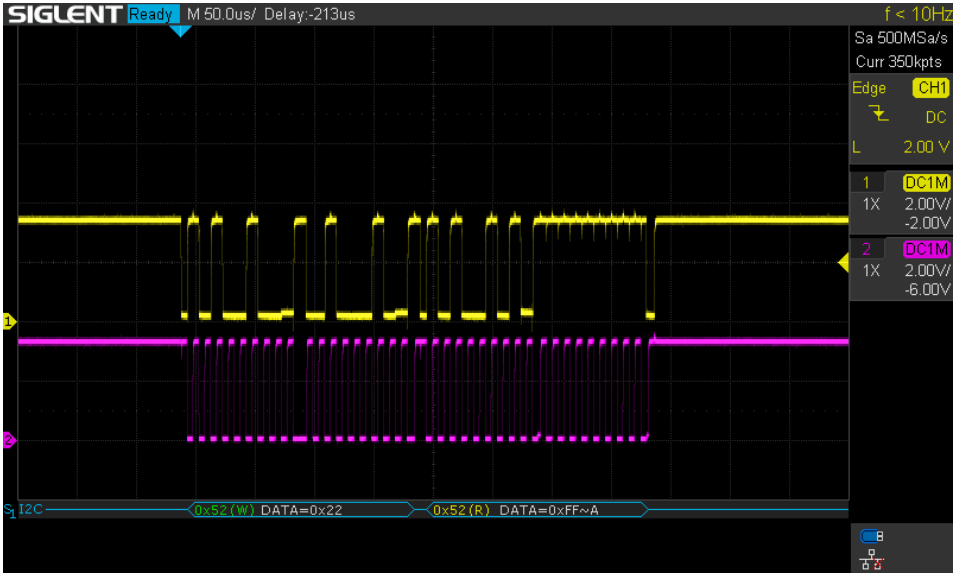
Oscilloscope

- Can show SCL and SDA with all the details
- Useful to check voltage levels, slopes, noise...
- Many models can visually decode I^2C and other protocols

Oscilloscope — NACK

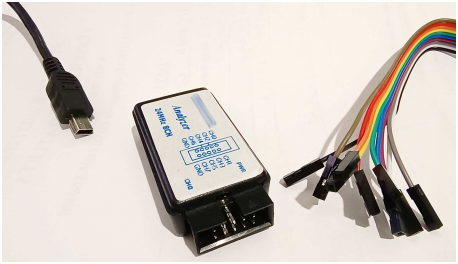


Oscilloscope — Register read

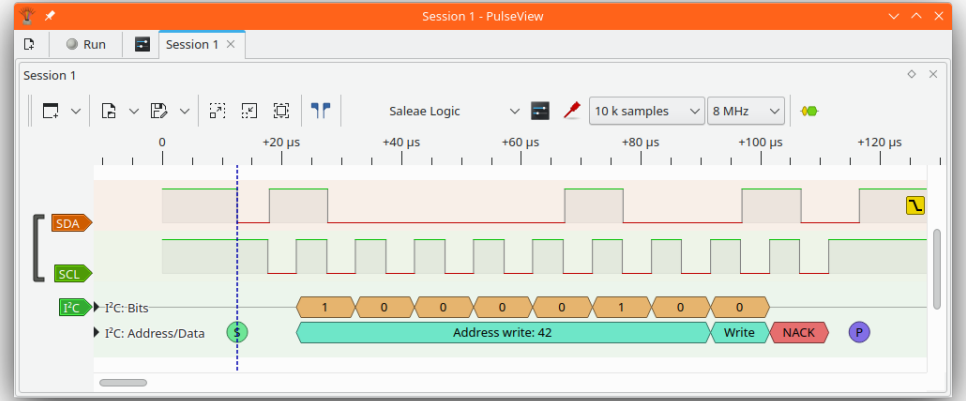


Logic analyzer

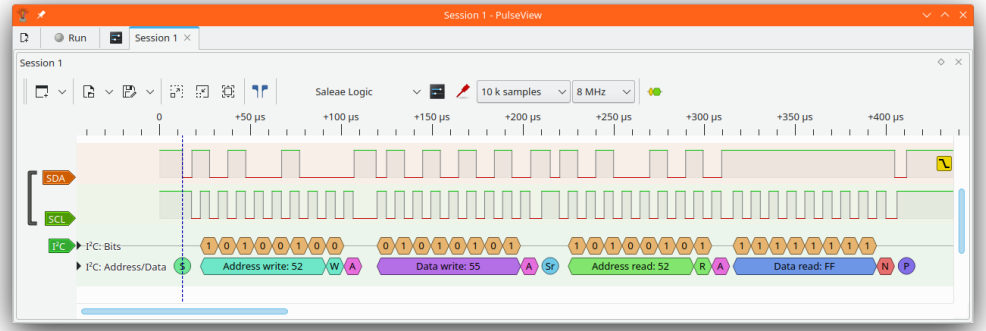
- **Sigrok** is suite of signal analysis software
  - https://sigrok.org
- **Pulseview**: a logic analyzer and oscilloscope, based on Sigrok
  - Visually decodes I²C and other protocols
  - https://sigrok.org/wiki/PulseView
- Open source, GPLv3+
- They work well with cheap acquisition devices



Pulseview — NACK



Pulseview — Register read



Troubleshooting

Troubleshooting tools

- Return code from `i2c_*()` functions — Never ignore errors!
- Kernel logs
- i2c-tools
- Oscilloscope or logic analyzer

No ACK from client — systematic

- Problem: a client **never** responds to transactions
  - i2c-tools symptom: `Error: Read failed`
  - Kernel internal APIs symptom: `-ENXIO`
- `i2cdetect`: a client (possibly yours) at any unexpected address?
  - Check address pins on client chip: datasheet, schematics
- `i2cdetect`: no client at any unexpected address?
  - Client not powered, held in reset, broken, unsoldered pin
- Oscilloscope: no activity on bus, SCL/SDA always high
  - Pinmux (I^2C adapter not reaching the pads)
  - Device tree: device under wrong bus
- Oscilloscope: no activity on bus, SCL/SDA always low
  - Missing pull-up resistors (external or internal)

No ACK from client — sporadic

- Problem: a client **sporadically** does not respond to transactions
  - i2c-tools symptom: `Error: Read failed`
  - Kernel internal APIs symptom: `-ENXIO`
- Oscilloscope: SCL/SDA lines return to high level too slowly
  - Weak pull-up
  - Workaround: reduce `clock-frequency` in device tree
- Oscilloscope: noise on SCL/SDA lines
  - Hardware must be fixed
- Oscilloscope: SCL/SDA delays incorrect
  - Propagation delay in lines at high speed? Review PCB
  - Tune `i2c-scl-internal-delay-ns`…
  - Workaround: reduce `clock-frequency` in device tree

No ACK from client after reset

- Problem: a client **sporadically** does not respond after unclean reset
  - Symptom: driver fails to respond, fails to probe
- No clean shutdown $\rightarrow$ driver could not set client to idle state
  - E.g. client left in the middle of a transaction, kernel starts a new one
- Reset all clients during boot
  - In hardware, if possible
  - In the bootloader otherwise

Bus busy

- Problem: SCL line held low
  - Symptom: `bus busy` in kernel logs

```
stm32f7-i2c 40015000.i2c: bus busy
stm32f7-i2c 40015000.i2c: Trying to recover bus
```

- Systematic
  - Short circuit / mounting problem
- Sporadic
  - Chip gone crazy
    - Bus recovery could fix it
  - Multimaster problem

Questions? Suggestions? Comments?

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https://bootlin.com/pub/conferences/

Extra slides

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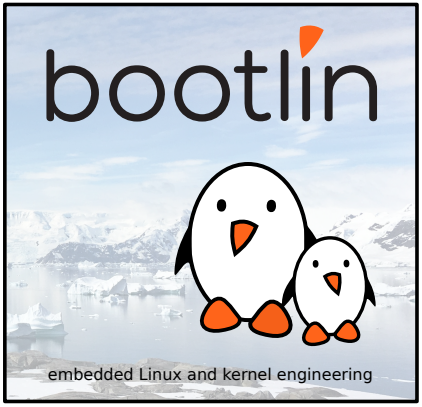
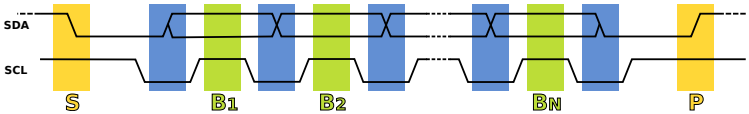


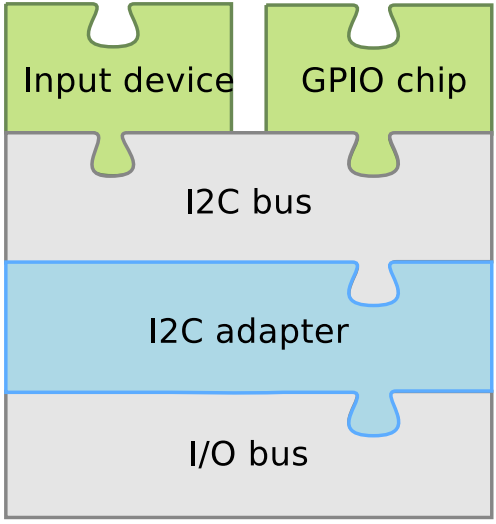
Bit-level communication



https://upload.wikimedia.org/wikipedia/commons/6/64/I2C_data_transfer.svg

- SCL low = move SDA
- SCL high = sample SDA
- Exception: Start / Stop condition

The driver model



I²C muxes and switches