I2C Hacking Demystified

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YOCTO LINUX KERNEL ZEPHYR INTEL GRAPHICS FOR LINUX QT DPDK
BLUE Z OSTRO GNOME CHROMIUM IOTIVITY Wayland Soletta

Creating, debugging and operating a custom I2C peripheral.

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Overview

- Typical applications
- Introduction to the I2C bus
- Custom slaves - why and how
- Master
- Debugging methodology and tools
- Example: steering a 4WD drone.
- Ideas for advanced bus configurations
- Recap
- Q/A

Typical Applications

- Interfacing with relatively slow peripherals.
  Ex: sensors, mechanical actuators.
- Controlling "fast" peripherals, that use other channels for exchanging data. Ex: codecs.

- In a PC, linux usually interacts over I2C with:
  - temperature and battery voltage meters;
  - fan speed controllers;
  - audio codecs.

- Multiple bus controllers, each at different speeds.

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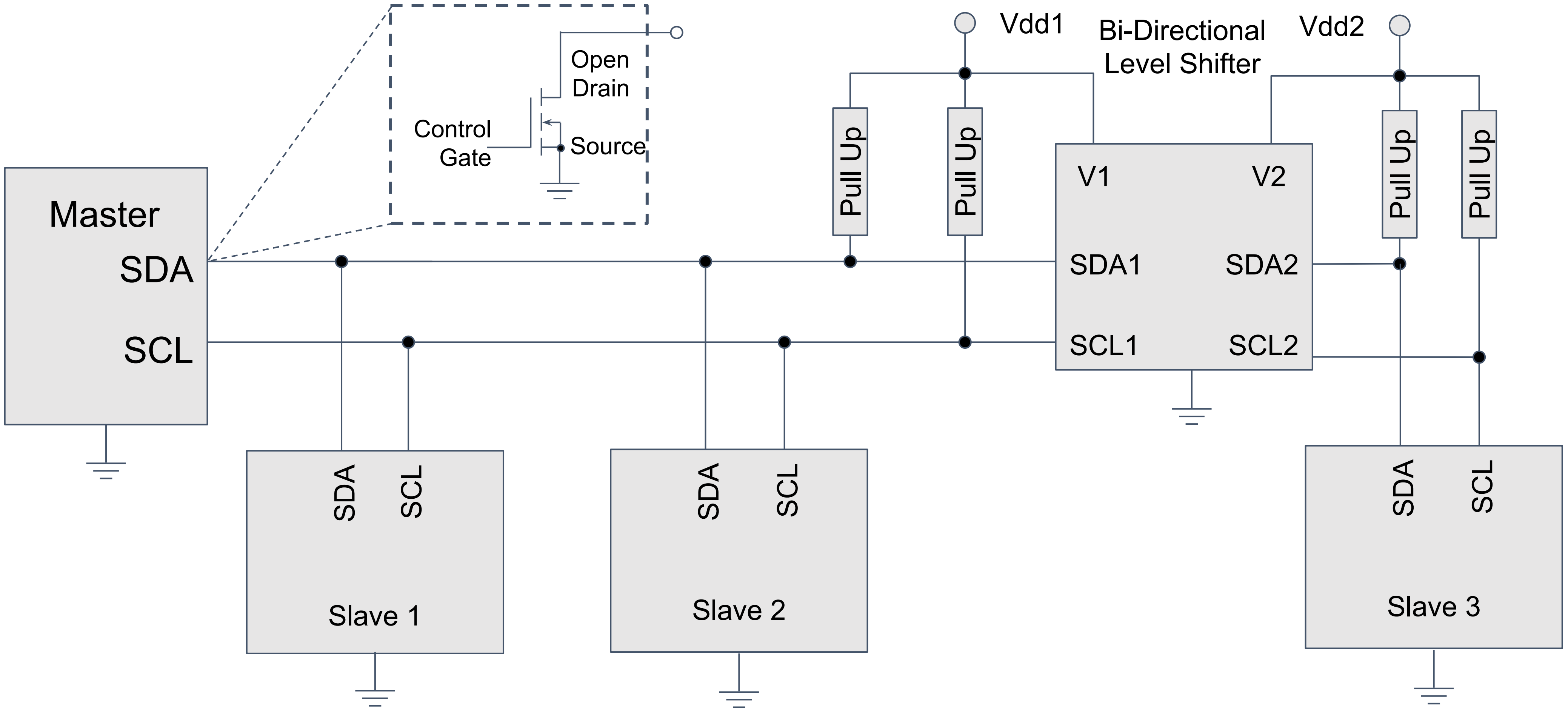
Introduction to the I2C Bus - Part 1

- Serial bus: http://www.i2c-bus.org/ http://www.robot-electronics.co.uk/i2c-tutorial
- Only 2 lines: Serial CLock and Serial DAta (plus ground).
- 4 speeds: 100kHz, 400kHz, 1MHz, 3.2MHz.
- Typically, 1 master device and 1 or more slaves.
- Communications are always initiated by a master device.
- Multiple masters can co-exist on the same bus (multi-master).
- Open-Drain: both SDA and SCL need pull-up resistors.

Introduction to the I2C Bus - Part 2

- "Clock Stretching"
  - The master controls SCL, but a slave can hold it down (because open drain), if it needs to adjust the speed.
  - The master must check for this scenario.
  - A slave can get stuck and jam the bus: need for reset lines from the master to the slave.
- Typically 7-bit addressing, but also 10 bit is supported.
- Logical protocol: actual voltage levels are not specified and depend on individual implementations.
  Ex: 1.8V / 3.3V / 5.0V

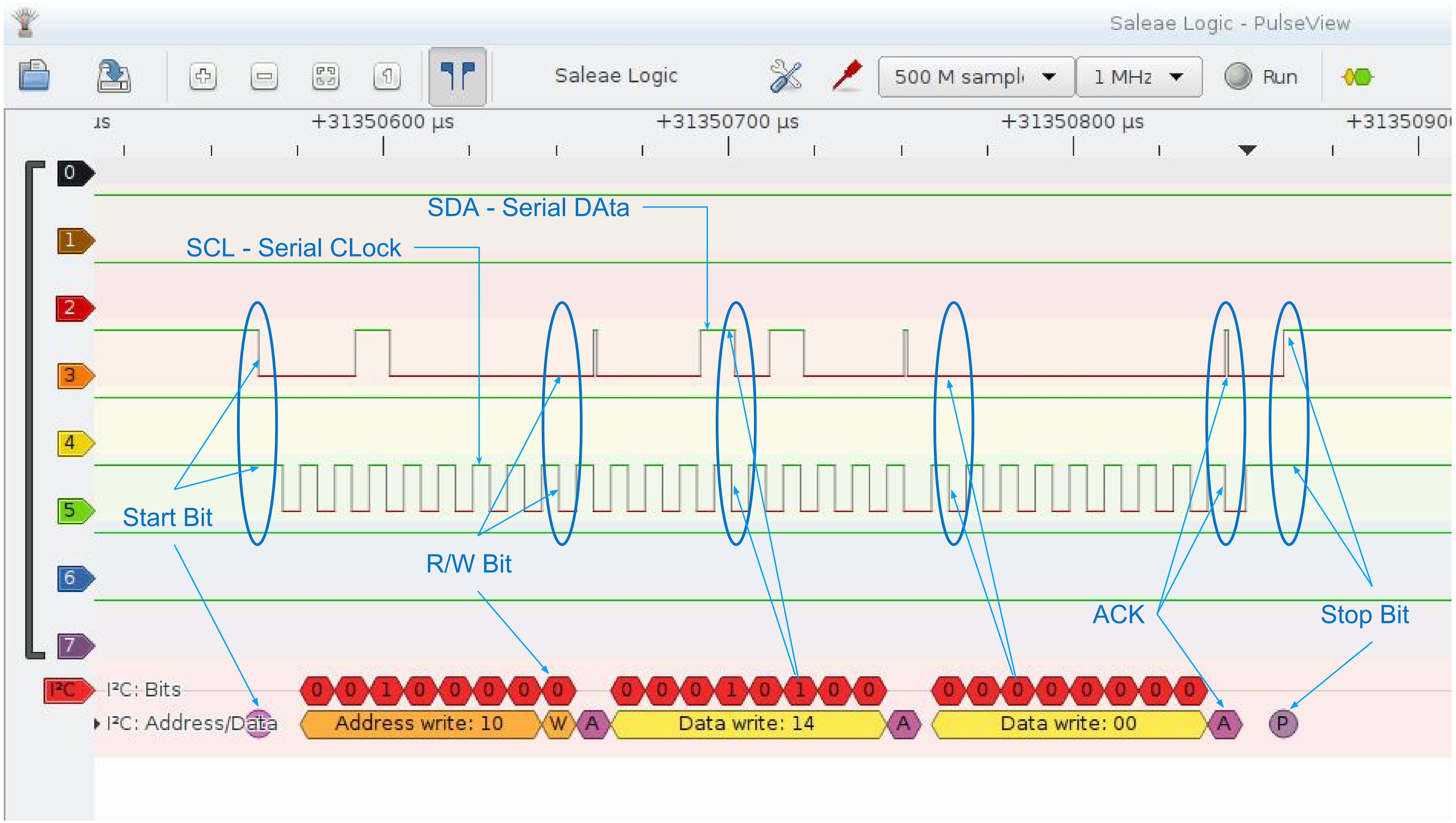
Example of bus configuration



Protocol (simplified)

- 2 messages: read / write
- Start / Stop bit - represented as “[“ and “]”
- Address: 7 or 10 bits
- R/W bit: R = 1 / W = 0
- Byte on the bus: (Address << 1 | R/W)
- Registers

Ex:
Write - [address/write_bit register value(s)]
Read - [address/write_bit register [address/read_bit read(s)]



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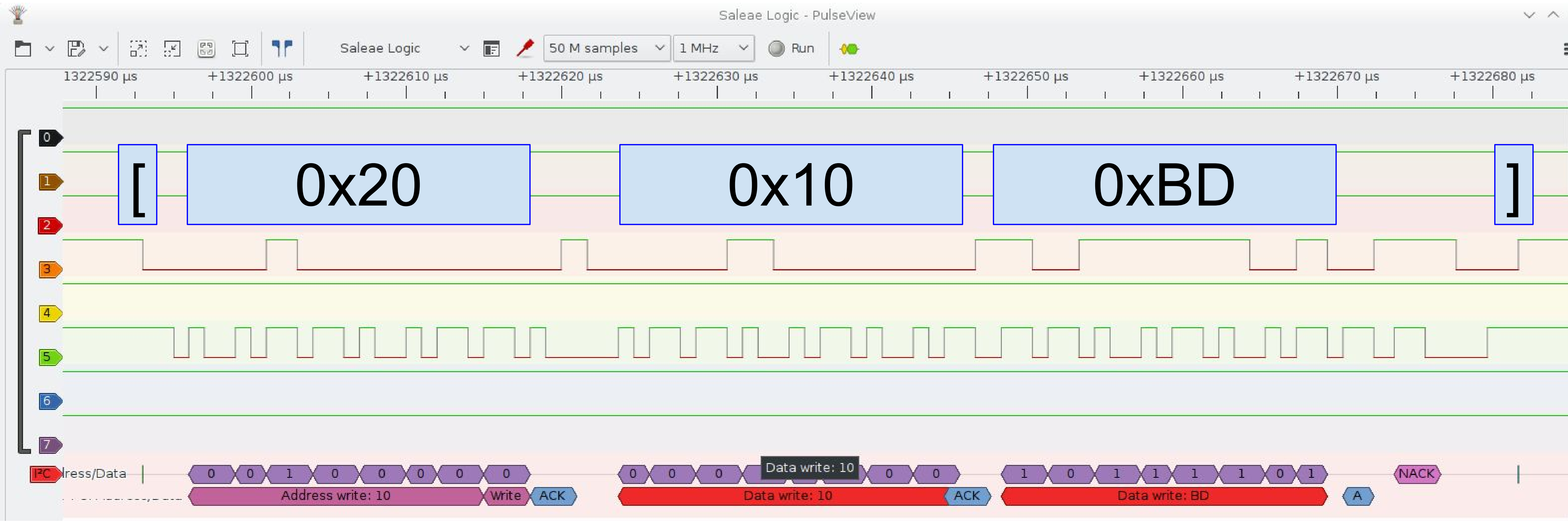
Example of bus write cycle.



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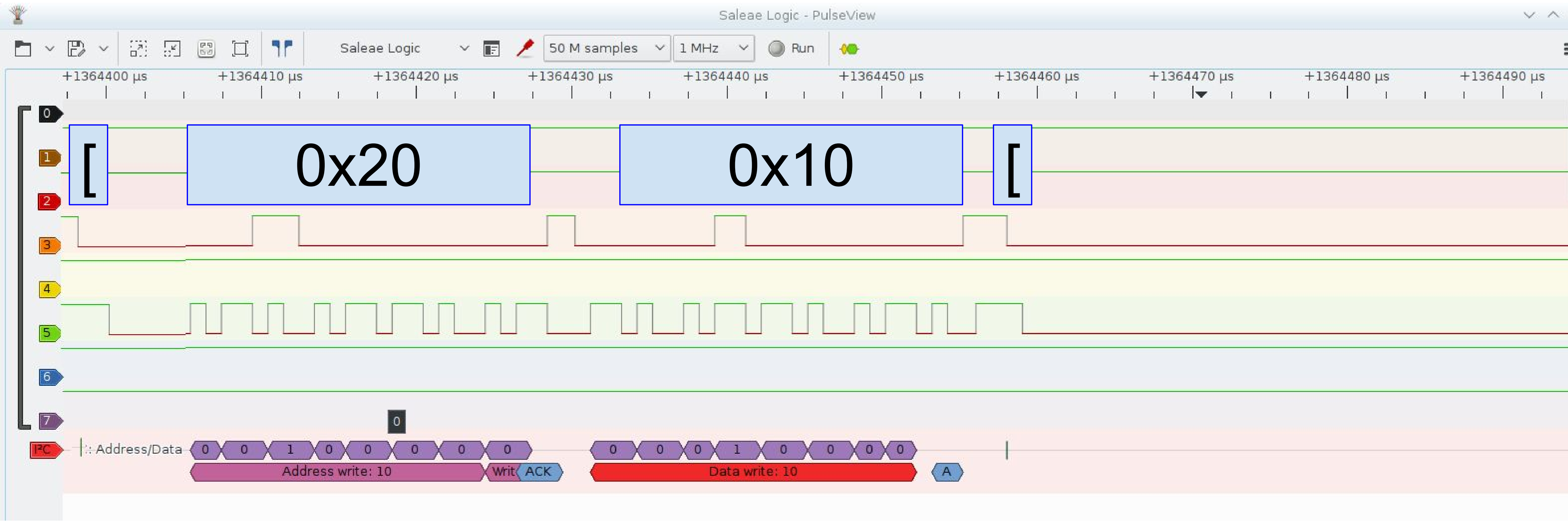
Example of bus read cycle - Part 1



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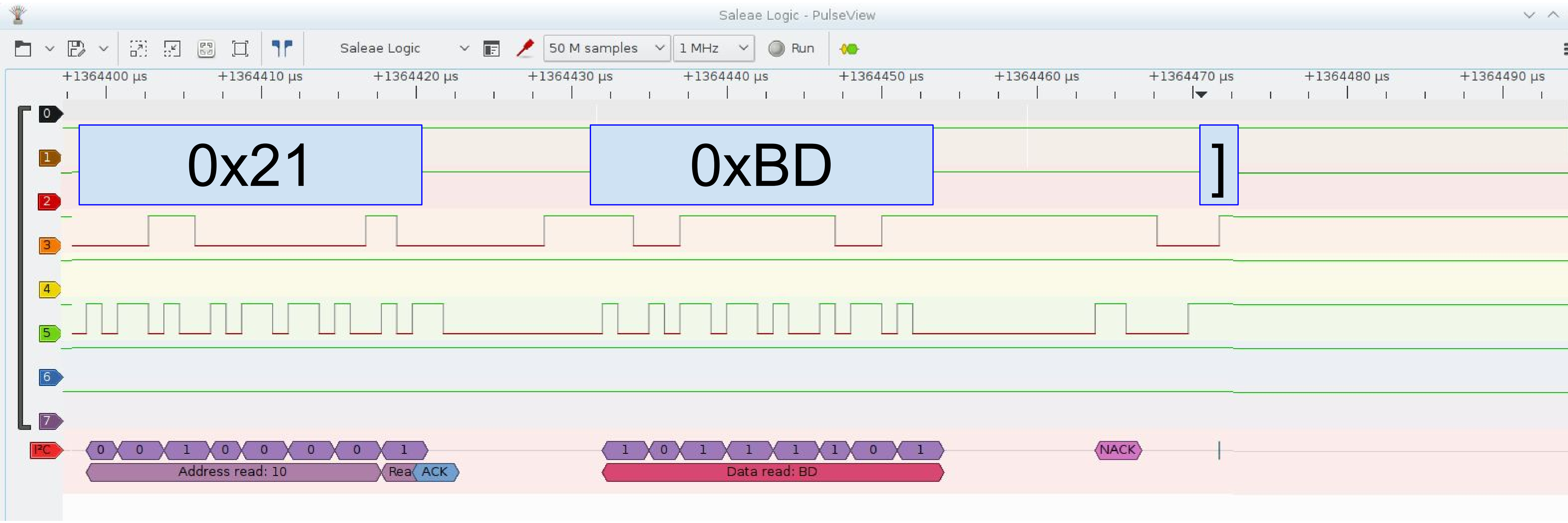
Example of bus read cycle - Part 2



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Custom Slaves

Why creating a custom I2C slave?

- Desired sensor/actuator unavailable with I2C interface.
- Less unique addresses available than slaves needed.
- Desired custom functionality on the slave:
    - Semi-autonomous reactions to stimuli.
    - Filtering/preprocessing input data.
    - Power optimization: custom “sensor hub” does the housekeeping while the main processor is idle.
    - Realtime response to inputs.
    - [*your imagination here*]

Custom Slaves

How to design a custom I2C slave?

- Define requirements (see previous slide).
- Choose microcontroller or microprocessor.
- Choose Scheduler or Operating System (if any).
- Define communication sub-protocol:
  - Define parameters and commands to be exchanged.
  - Organize them into "registers" and choose a free address.

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Design of the I2C Master

Key design criteria:

- Weight/Dimensions.
- Required computational power and average latency.
  - PC-like device
  - Embedded device, typically headless.
- Preferred programming language: interpreted vs compiled.
- Availability of busses/gpios for driving the slave(s):
  - GPIOs only: bitbang the protocol
  - I2C: user-space application vs kernel driver.
  - No GPIOs/I2C interfaces available: USB to I2C adapter.

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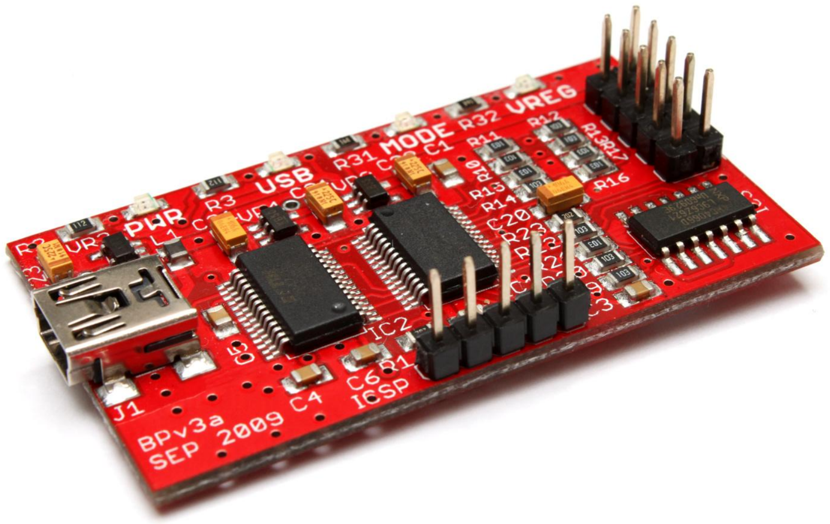
Debugging: Divide and Conquer.

- Take direct control of the bus with an ad-hoc device. Examples:
    - Bus Pirate (useful also for other busses)
    - USB to I2C Master adapter, also based on the FTDI FT232R chip.
    - Custom device (could be a separate project).
- Snoop the bus with a logic analyzer or a scope/advanced meter. Examples:
    - sigrok/pulseview with compatible logic analyzer
    - 2-channels standalone scope/meter
- Use slave-specific In Circuit Debugger/In Circuit Emulator: Example:
    - AVR Dragon for AVR chips (Arduino UNO, Nano, Mini, MiniPro)

Bus Pirate



- Primarily for development purposes.
- Can both sniff the bus and drive it.
- Console interface over serial (ttyACM) port, including macros, or programmatic access for several programming languages.
- Built-in pullup resistors and voltage sources (5V / 3.3V)
- Supports many other protocols.

http://dangerousprototypes.com/docs/Bus_Pirate

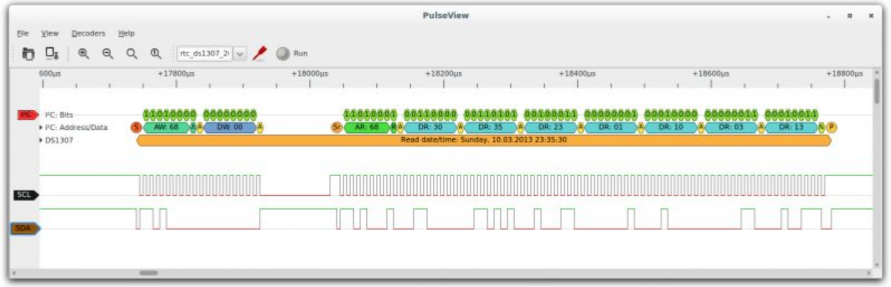
https://en.wikipedia.org/wiki/Bus_Pirate

USB to I2C adapter

- Small footprint.
- Suitable for permanent installations.
- No need for special connections on the host: it can be used to interface with a typical PC.
- Variant available that is also SPI-capable.
- No console interface, only serial binary protocol.
- Requires protocol wrapper.

`http://www.robot-electronics.co.uk/htm/usb_i2c_tech.htm`

sigrok/pulseview



- De-facto standard for PC-driven measurements on linux (but available on other OSes too).
- Support for vast range of logic analyzers, scopes and meters.
- Various protocol decoders, including I2C.
- Useful for visualizing the logical signals and debugging protocol errors.
- Even very low end, inexpensive HW can provide a whole new dimension to debugging.

https://sigrok.org

https://sigrok.org/wiki/PulseView

https://sigrok.org/wiki/Supported_hardware

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- Improvement Ideas
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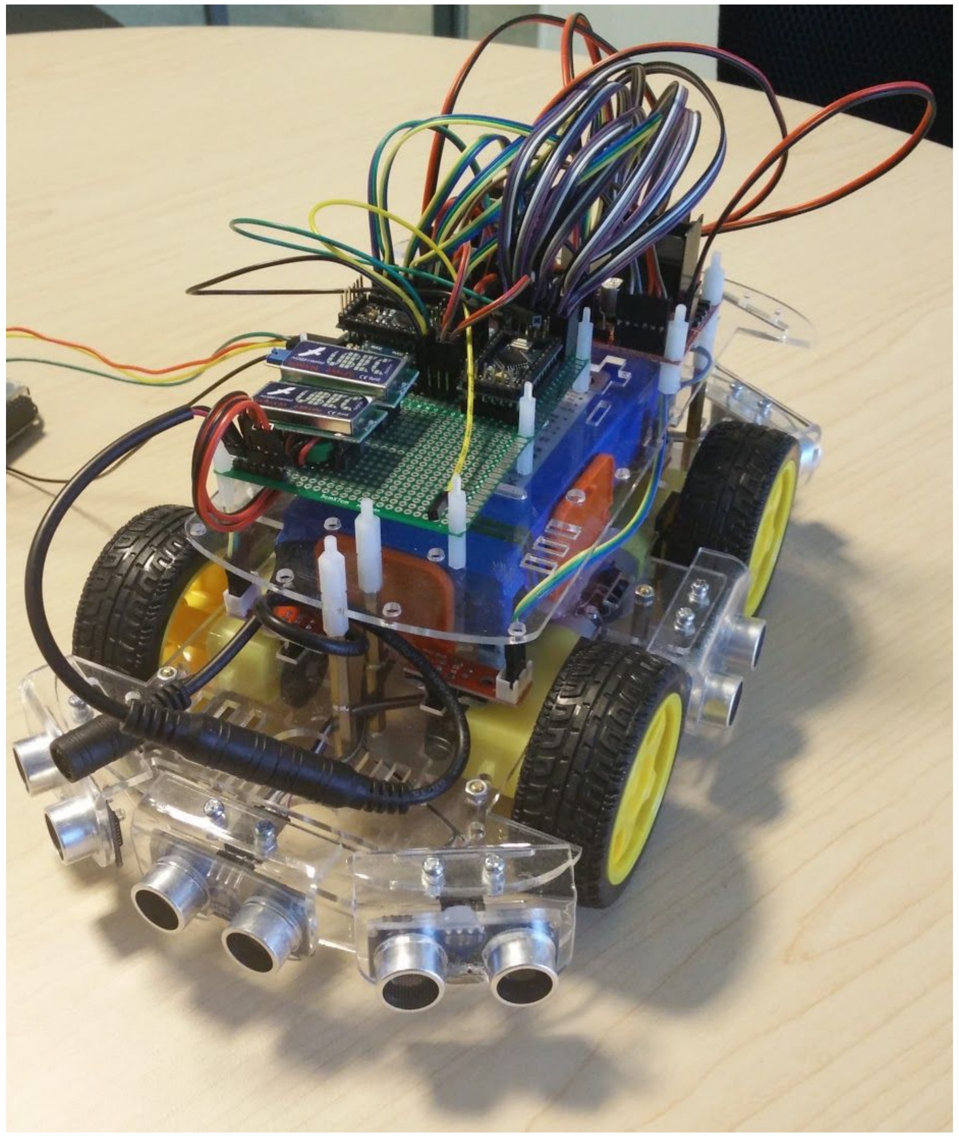
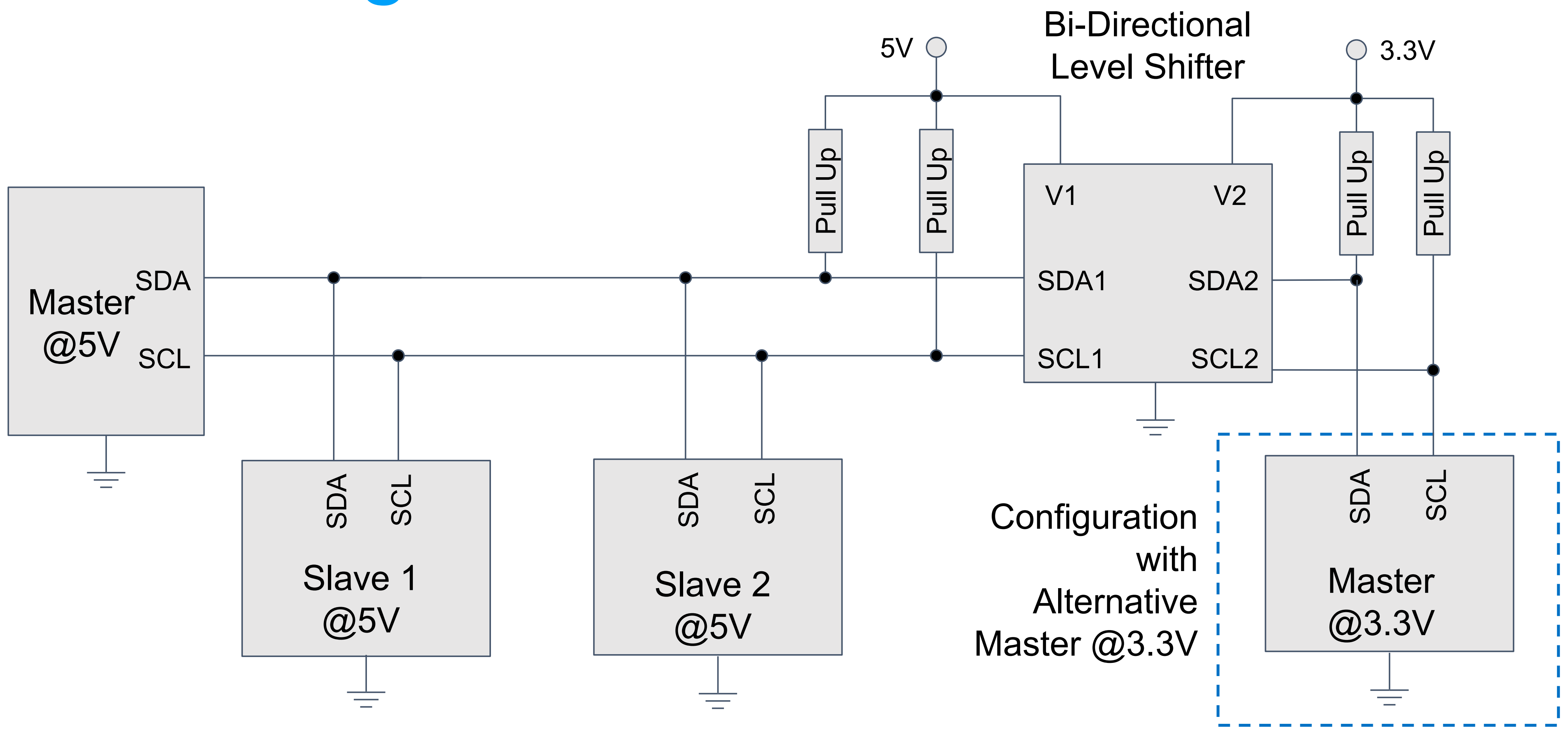


Bus configuration



Custom Slaves

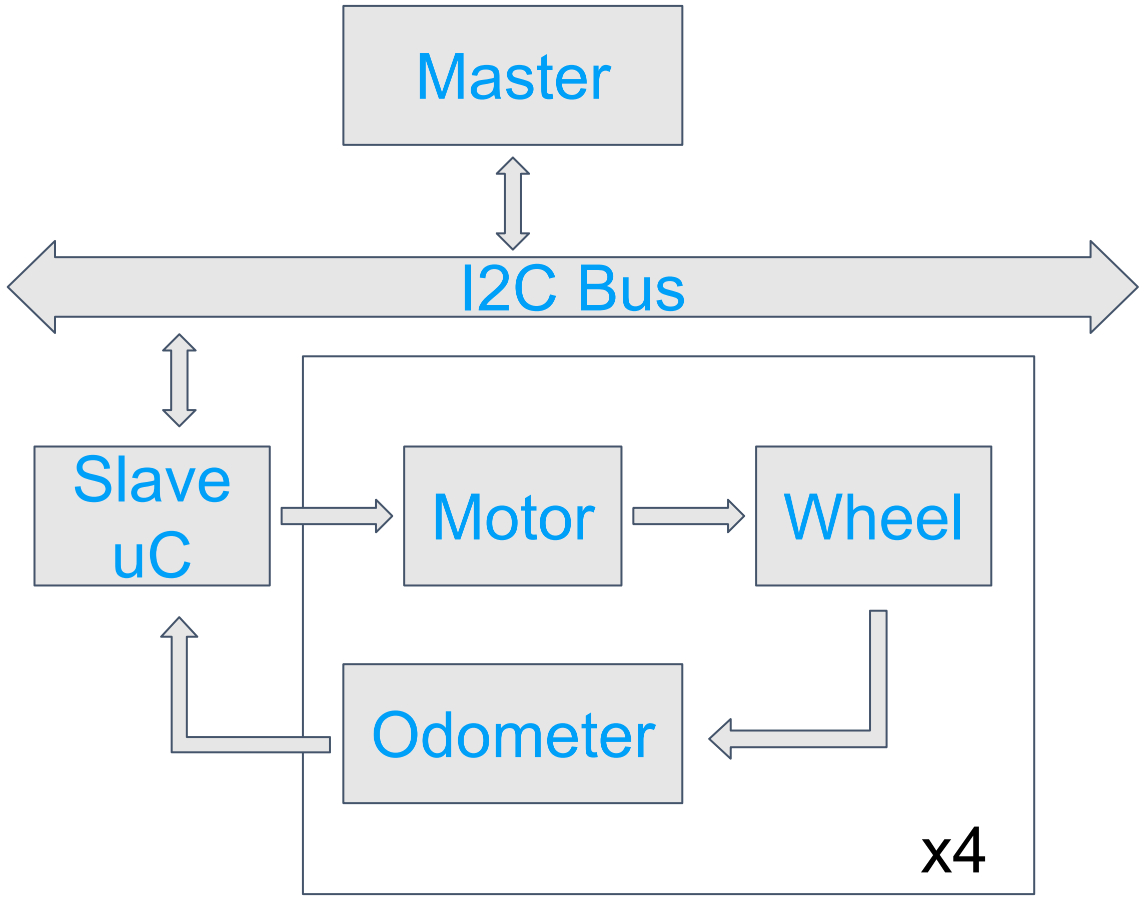
How to design a custom I2C slave?

- Define requirements.
- Choose microcontroller or microprocessor.
- Choose Scheduler or Operating System (if any).
- Define communication sub-protocol:
  - Define parameters and commands to be exchanged.
  - Organize them into “registers” and choose a free address.

Example: Steering a 4WD Drone

The I2C slave:

- Controls the amount of **torque** applied to each wheel.
- Controls the **direction** each wheel spins.
- Measures the **rotation speed** of each wheel through an optical encoder (Odometer).
- Exposes the parameters above to the I2C Master.



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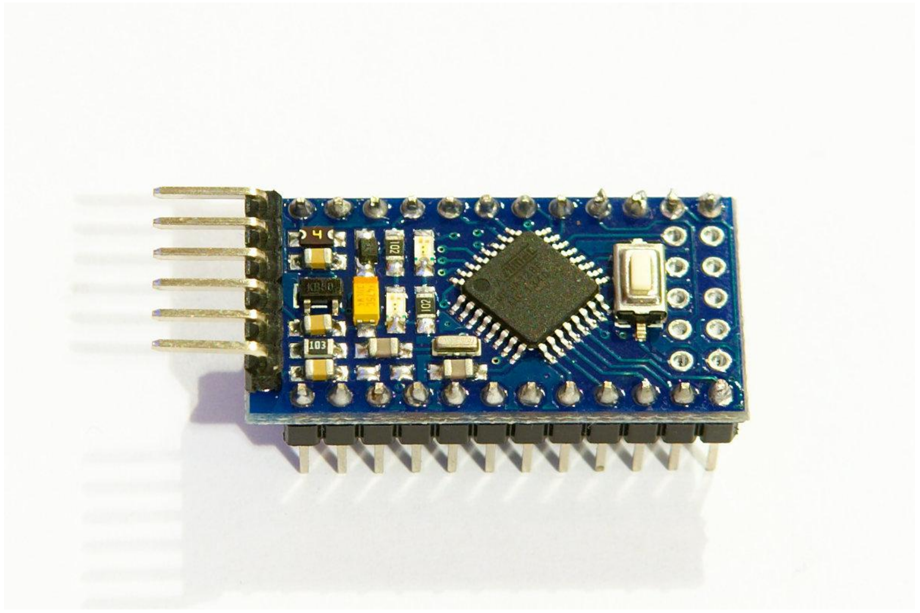
Selecting the Slave: Arduino Mini Pro (AVR328P)



- Enough pins/functions to provide for each wheel:
  - 1 PWM output with independent configuration of the duty-cycle.
  - 2 GPIOs for selecting: Forward, Reverse, Idle, Lock
  - 1 GPIO for registering odometer input as IRQ.
- I2C HW block for interrupt-driven i2c exchanges.
- Dedicated pins for SPI-based programming.
- Small footprint.
- Low Cost.
- The clone represented in the picture has layout optimized for DIL socket mounting.

`https://www.arduino.cc/en/Main/ArduinoBoardProMini`

Slave-specific ICD: AVR Dragon

- Supports various programming modes, included SPI programming, through AVRDude.
- Doesn’t interfere with normal AVR operations, so it can be left plugged into the system.
- After enabling debugWire interface, it allows configuring HW/SW breakpoints, by a dedicated backend for gdb/ddd.

http://www.atmel.com/webdoc/avrdragon/

http://www.nongnu.org/avrdude/

http://www.larsen-b.com/Article/315.html

Custom Slaves

How to design a custom I2C slave?

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Selecting the OS: ChibiOS

- RTOS: preemption, tasks, semaphores, dynamic system tic, etc.
- Small footprint: link only used code/data.
- Distinction between RTOS and BSP through HAL.
- GPLv3 for non-commercial use.
- Actively developed, but already mature.

However it had limited BSP support for AVR, lack of:

- interrupts driver for AVR GPIOs (added).
- I2C support for AVR slave mode (custom).

http://www.chibios.org/dokuwiki/doku.php

https://github.com/igor-stoppa/ChibiOS/tree/car/

Custom Slaves

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Communication Parameters - 1

For each wheel:

- **Duty Cycle** of the PWM signal used to drive it - 1 byte.
  0xFF = max torque / 0x00 = no torque.

- **Direction** of rotation - 1 byte.
  0x00 = idle / 0x01 = reverse / 0x02 = forward / 0x03 = locked

- **Average period** in between slots of the optical encoder - 2 bytes.
  Writing anything resets the measurement.

Communication Parameters - 2

- Parameter Index - 1 nibble:
  - 0 = Duty Cycle
  - 1 = Direction
  - 2 = Average Period
- Wheel indexes - 1 nibble:
  - 0 = Left Rear
  - 1 = Right Rear
  - 2 = Right Front
  - 3 = Left Front
  - 4 = All

Custom Slaves

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Sub-Protocol: registers

Register format: 0xαβ

- α = Parameter Index
- β = Wheel Index

Address: 0x10

Bus Pirate format:

```
[ = start bit
] = end bit
r = read byte
address times 2, for R/W bit
```

Example - in Bus Pirate Format:

```
[ i2c_addr reg_addr=(parm,wheel) reg_value]
[0x20 0x20 0x02]  Left Rear Forward
[0x20 0x21 0x01]  Right Rear Backward
[0x20 0x22 0x01]  Right Front Backward
[0x20 0x23 0x02]  Left Front Forward
[0x20 0x14 0xFF]  Wheels set to max torque


The car spins clockwise.
```

Design of the I2C Master

Key design criteria:

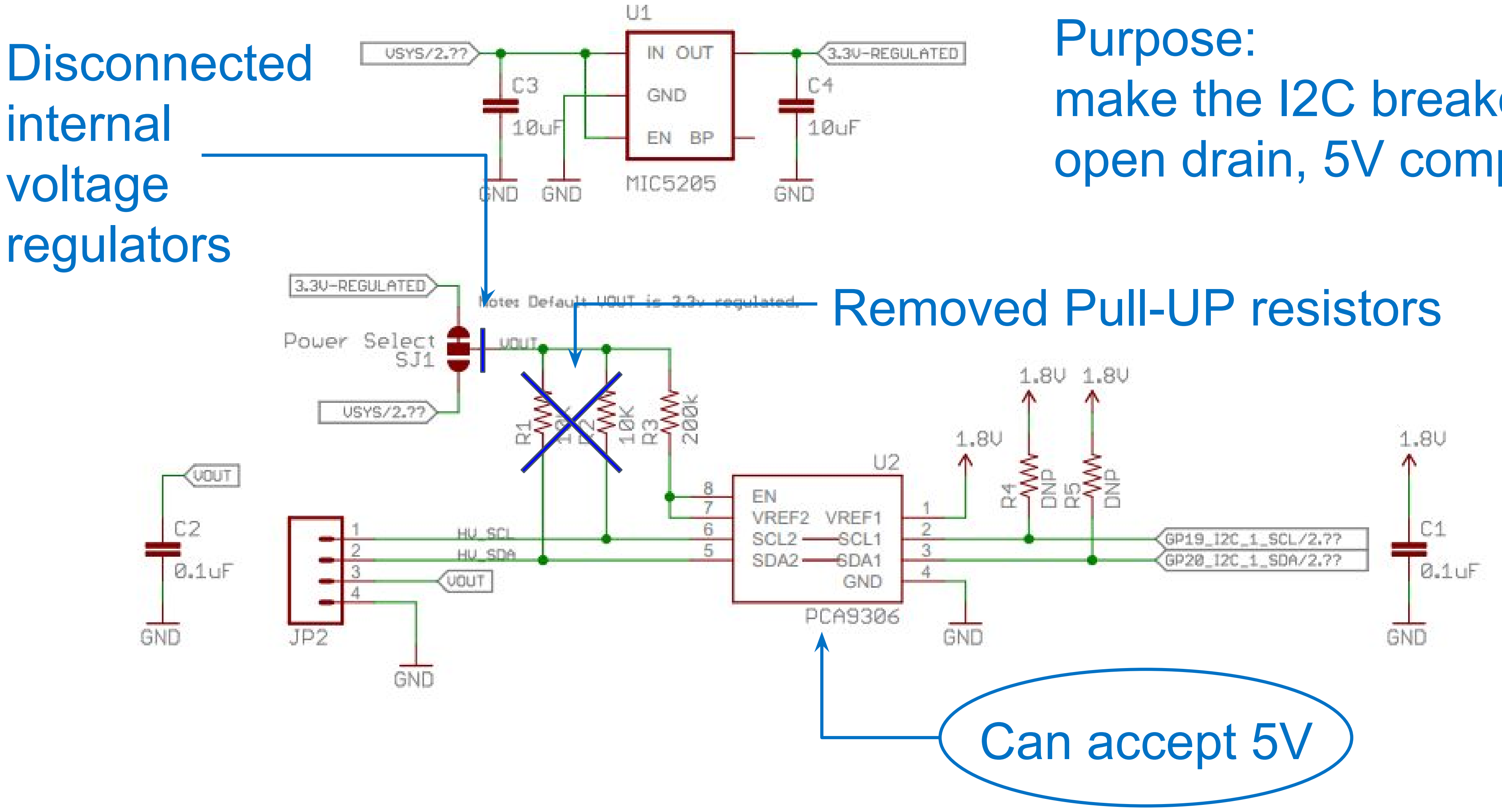
- Weight/Dimensions: must fit on the drone.
- Required computational power and average latency
  - Embedded device, it can provide enough computational power.
- Availability of busses/gpios for driving the slave(s):
  - Native I2C available on most candidates
  - user-space application is sufficient:
    no requirement for extremely low latency, might change later on
- Preferred programming language: interpreted vs compiled.

Master:
Intel Edison

- x86-64
- Built-in connectivity:
  - Wifi
  - Bluetooth
  - OTG - Ethernet over USB
  - Serial Console
- I2C available through add-on breakout board, normally @3.3V, here hacked @5V

5V Mod for Sparkfun I2C Breakout

Purpose:
make the I2C breakout open drain, 5V compatible



OS: Linux Flavors

Official Edison distro (based on Poky/OE) `https://software.intel.com/en-us/iot/hardware/edison/downloads`

Ubilinux (Debian port)
`http://www.emutexlabs.com/ubilinux`

[Ostro Project using libmraa](https://download.ostroproject.org/builds/ostro-os/latest/images/edison/)
https://download.ostroproject.org/builds/ostro-os/latest/images/edison/
`http://iotdk.intel.com/docs/master/mraa/`

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From Bus Pirate format to Python

Example - in Bus Pirate Format:

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[0x20 0x22 0x01]  Right Front Backward
[0x20 0x23 0x02]  Left Front Forward
[0x20 0x14 0xFF]  Wheels: max torque
```

The car spins clockwise.

Note:

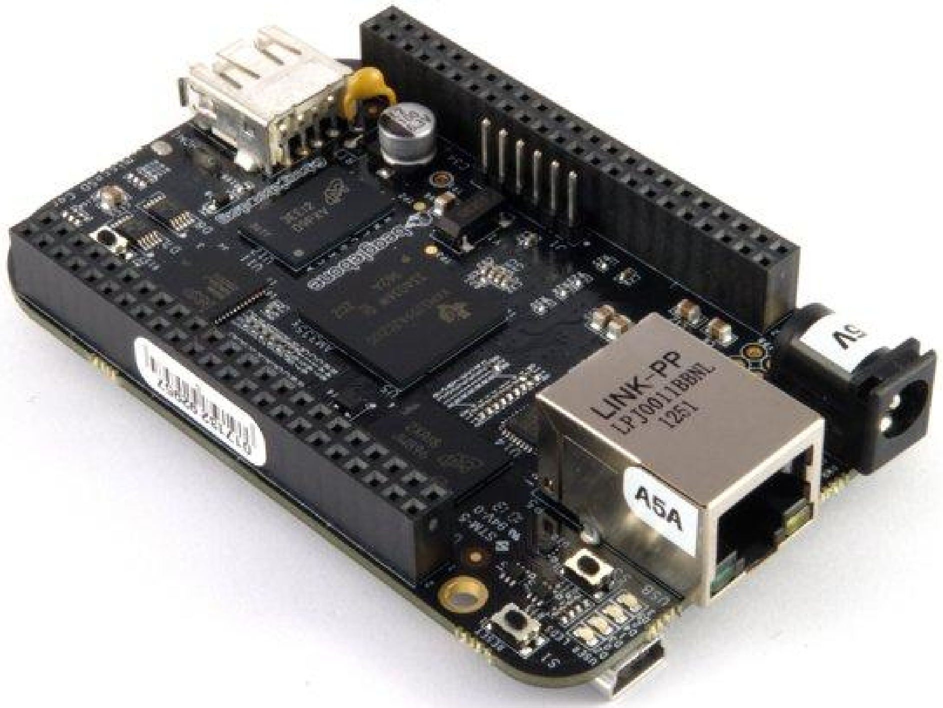
Bus Pirate simply dumps data on the bus, so the address 0x10 must be shifted left because of the R/W bit.

Example - Python with libmraa:

```
#!/usr/bin/python
import mraa
x = mraa.I2c(1) # Select the correct I2C bus
x.address(0x10) # The library does the shift
x.writeReg(0x20, 0x02) # Left Rear Forward
x.writeReg(0x21, 0x01) # Right Rear Backward
x.writeReg(0x22, 0x01) # Right Front Backward
x.writeReg(0x23, 0x02) # Left Front Forward
x.writeReg(0x14, 0xFF) # Wheels: max torque
```

The car spins clockwise.

Alternative Master: BeagleBone Black



- Cortex A8
- Built-in connectivity:
  - Ethernet
  - Ethernet-over-USB
  - Serial Console
- I2C available through standard connector, open drain, compatible with @3.3V
- C userspace program using libi2c.

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Ideas for improvement

- Add multi-master support
  - The current implementation is efficient wrt Slave time because it is event-driven and there is action happens only as result of an IRQ firing (no polling).
  - The Master, however, **is** polling the slave and polling is never a particularly good idea:
    - poll too often and it will overload the system
    - poll too seldom and important events might escape the window-of-opportunity
- Add arbitrary capability to R/W memory areas over I2C
  - live debugging of the I2C Slave.
  - Useful for memory mapped peripherals.
  - Could be used in conjunction with the memory map & linker scripting.

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Questions?

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