Introduction to Bare Metal Rust

Bare Metal Embedded in 2 Minutes

- Direct Interaction with the environment
  - Analog or digital signals, communication
- No Operating System, no dynamic memory
- Relatively low memory and processing power
- “Embedded”: Computer is implementation detail
  - Ticket machine? Door knob? Gas pedal?

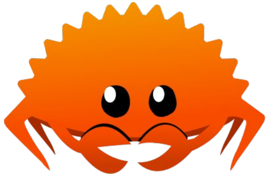
Bare Metal Embedded in 2 Minutes

- Concurrency via interrupts
- Singleton Pattern: “There are REALLY only 3 serial ports”
- Challenge: Mapping of resources
  - Timer 7 -> ADC Channel 3 -> DMA [Peripheral to Memory]
- Modules can **own** resources
  - Control Module: ADC, Timer/PWM
  - Sensor driver: GPIOB12, UART1

Rust in 3 Minutes

- Modern (primarily) systems language
- Strict type system enforces correct usage of shared resources
- Strict compiler is getting friendlier all the time (but still strict)
- Friendly and extensible tooling (test, bench, metrics, dependencies, linting, …)
- Dependency management: lots of small, interoperating libraries (some big ones around too, but no Qt)

Rust in 3 Minutes – Goals and Tradeoffs

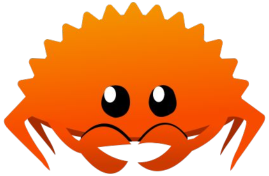


- Binaries and Performance like C
- Type System inspired by Haskell (Hindley–Milner)
- Ergonomics inspired by Python
- Tooling like Javascript/node.js
- “Unique” learning curve
- Compile-times like C++ (sometimes worse)

www.rust-lang.org

Rust in 3 Minutes – Guarantees

- No SEGFAULTS
  - Panic: Structured Deconstruction
- No Undefined Behaviour
- No Data Races
- Zero-Cost Abstractions



www.rust-lang.org

Rust + Bare Metal = ❤️ ?

How do the strengths of Rust apply to programming Bare Metal?

- Low Memory usage, no runtime or heap required
- Safe error handling without heap or exceptions
- Memory Safety
- Tooling (Toolchain Management, Testing, Flashing)
- Architecture-specific optimizations by LLVM
- But: Some targets not supported by LLVM
  (recently got AVR and XTENSA)

Libraries and Ecosystem

Basics: **P**eripheral **A**bstraction **C**rates

- Similar purpose to C register definition headers (registers/offsets/fields...)
- API forces Read/Write/ReadWrite access for registers
- Generated from vendor-supplied SVD files (ARM-Standard)

https://www.keil.com/pack/doc/CMSIS/SVD/html/index.html

https://github.com/rust-embedded/svd2rust

Basics: Peripheral Abstraction Crates

```
I2C1.icr.reset();

I2C1.timingr.write(|w| w.bits(0x0000020B));
I2C1.cr2.modify(|_, w| w.autoend().set_bit());
I2C1.oar1.modify(|_, w| w.oa1en().clear_bit());
I2C1.oar2.modify(|_, w| w.oa2en().clear_bit());
I2C1.cr1.modify(|_, w| w.nostretch().clear_bit());
I2C1.cr1.modify(|_, w| w.pe().clear_bit());
```

Closures are optimized away to single instructions

Family and Board Support Crates

Friendly APIs based on PACs for ADC, Timer, I2C, etc.

Chip specifics: DMA, extension traits, special peripherals, …

Whole families covered by feature flags (for example, stm32f4)

github.com/stm32-rs/stm32f4xx-hal

github.com/stm32-rs/stm32f3xx-hal

github.com/nrf-rs/nrf-hal

github.com/rp-rs/rp-hal/tree/main/rp2040-hal

hal-implementation-crates

Family and Board Support Crates

```
let sda_pin = pins.gpio18.into_mode::<I2C>();
let scl_pin = pins.gpio19.into_mode::<I2C>();
// let not_an_scl_pin = pins.gpio20.into_mode::<I2C>(); // fails

// Create the I²C struct, using the two pre-configured pins.
// Fails to compile if the pins are in the wrong mode,
// or if this I²C peripheral isn't available on these pins
let mut i2c = i2c1(pac.I2C1, sda_pin, scl_pin, 400.kHz());

// Write three bytes to the I²C device with 7-bit address 0x2C
i2c.write(0x2c, &[1, 2, 3]).unwrap();
```

This example from rp-hal on GitHub

Shared Abstractions

Some abstract interfaces to SPI, I2C, ADC, Timers, Serial, …

Why?

- Reusability, learnability, portability
- Platform-agnostic drivers

Family and Board Support Crates implement these interfaces!

However, currently only blocking APIs.

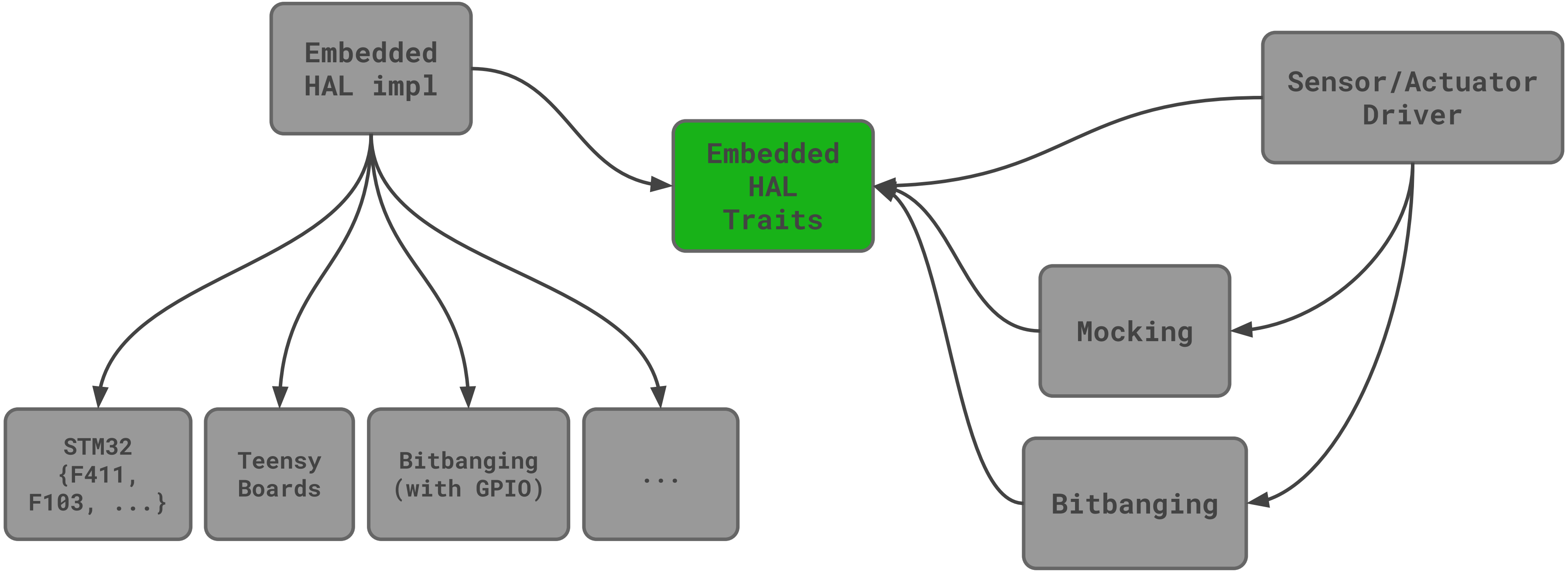
github.com/rust-embedded/embedded-hal

Portable Drivers: Bitbanging

```
use bitbang_hal::i2c::*;

let timer_i2cbb1 = Timer::tim2(dp.TIM2, 200.khz(), &mut rcc);

// Configure I2C with 100kHz rate
let i2cbb1 = I2cBB::new(i2cbb1_scl, i2cbb1_sda, timer_i2cbb1);

let mut sdp8xx1 = Sdp8xx::new(i2cbb1, 0x25, delay.clone());
```

Bitbanging Code

Embedded HAL Birds-Eye View

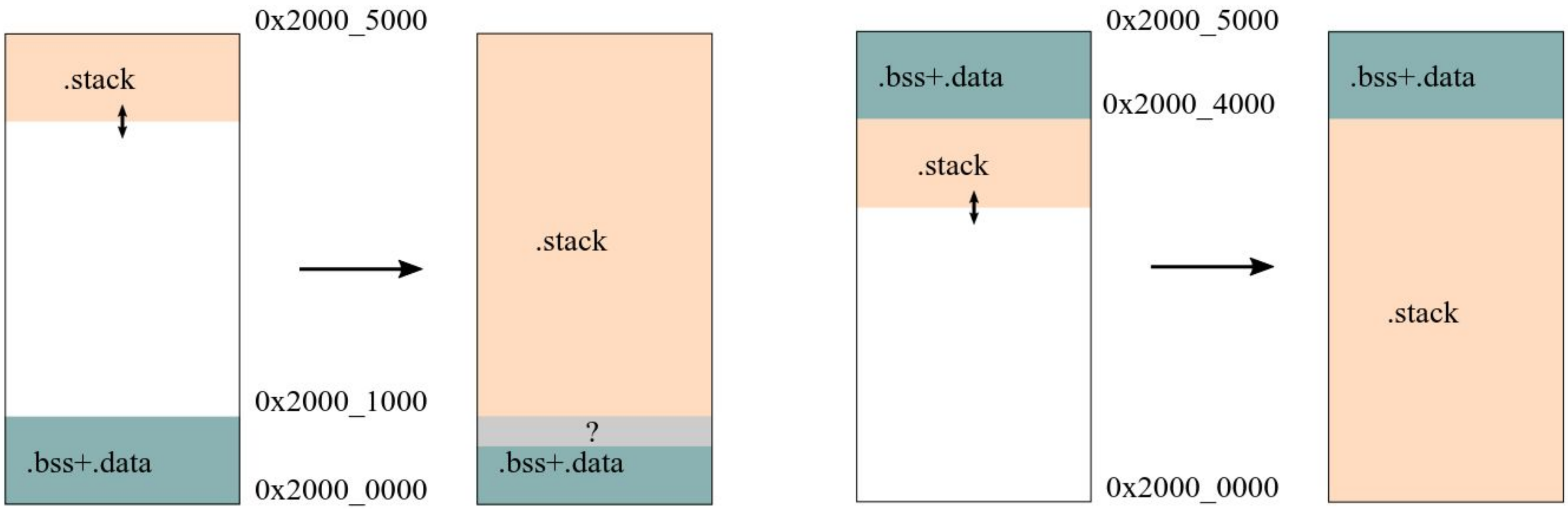


Tooling

Rust Embedded Tooling: flip-link

knurling-rs

flip-link: swap .stack and .data+.bss. Triggers **HardFault** on stack overflow.



Rust Embedded Tooling: defmt

knurling-rs

- defmt: Deferred Formatting on host system + “compressed” strings
- Transfer only raw data, not formatted strings
- Not **“temperature is {}”**, but **ID**, which is known on host
- Full-featured logging (levels, timestamps, panic/assert print, …)

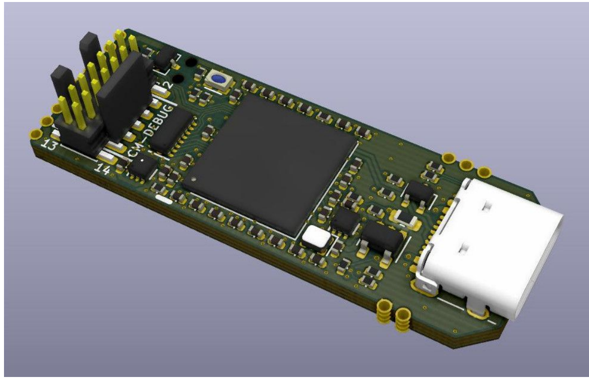
Framework	`.text`	**relative size**	`.rodata`	**relative**	`.text`+`.rodata`	**relative**
`core::fmt`	10348	1.0	3840	1.0	14188	1.0
`defmt`	1272	0.1229	360	0.0938	1632	0.1150

Rust Embedded Tooling: probe-rs

knurling-rs

probe-rs: Rust Toolset, Interaction with MCUs via debug probes

- Arm + Risc-V supported (SWD + JTAG)
- Flash, debug, inspect core, dump memory, stacktrace
- Microsoft DAP support: editor-agnostic debugging



https://github.com/probe-rs/hs-probe

probe.rs

Rust Embedded Tooling: probe-rs

knurling-rs

```rust
use probe_rs::Probe;

// Get a list of all available debug probes.
let probes = Probe::list_all();

// Use the first probe found.
let probe = probes[0].open()?;

// Attach to a chip.
let session = probe.attach("nrf52")?;

// Select a core.
let core = session.core(0)?;

// Halt the attached core.
core.halt()?;
```

Rust Embedded Tooling: cargo-bloat

```
> cargo bloat --release
Analyzing target/thumbv7em-none-eabi/release/client

File  .text    Size        Crate Name
0.1% 10.4% 2.1KiB   rtic_core <(T1,T2,T3,T4,T5,T6,T7)
0.0%  4.5%   962B      shared shared::setup_radio_with_payload_len
0.0%  4.4%   932B   rtic_core <(T1,T2,T3,T4,T5,T6)
0.0%  3.4%   720B         std core::fmt::Formatter::pad
0.0%  2.2%   476B stm32wlxx_hal stm32wlxx_hal::rtc::Rtc::set_date_time
0.0%  2.0%   428B   defmt_rtt <Logger as defmt::traits::Logger>::write
0.0%  2.0%   426B   rtic_core <(T1,T2,T3,T4,T5,T6)
0.0%  1.8%   388B         std core::fmt::write
0.0%  1.7%   352B stm32wlxx_hal stm32wlxx_hal::rcc::sysclk
0.0%  1.7%   350B stm32wlxx_hal <Status as defmt::traits::Format>::format
```

Rust Embedded Tooling: Tarpaulin

Simple line coverage analysis

```
May 16 23:31:18.162  INFO cargo_tarpaulin::report: Coverage Results:
|| Tested/Total Lines:
|| src/command.rs: 12/14
|| src/lib.rs: 95/125
|| src/product_info.rs: 31/34
|| src/sample.rs: 28/31
|| src/test.rs: 162/163
||
89.37% coverage, 328/367 lines covered
```

crates.io/crates/cargo-tarpaulin

Rust Embedded Tooling: Tarpaulin

github.com/barafael/cd74hc4067/blob/main/coverage.pdf

```rust
impl<P, E> CD74HC4067<P, E, EnabledState>
where
    P: OutputPin,
    P: OutputPin,
    P: OutputPin,
    P: OutputPin,
    E: OutputPin,
{
    /// Disable the mux display by pulling `pin_enable` high
    pub fn disable(mut self) -> Result<CD74HC4067<P, E, DisabledState>, Error<P, E>> {
        self.pin_enable.set_high().map_err(Error::EnablePinError)?;
        Ok(CD74HC4067 {
            pin_0: self.pin_0,
            pin_1: self.pin_1,
            pin_2: self.pin_2,
            pin_3: self.pin_3,
            pin_enable: self.pin_enable,
            state: PhantomData::<DisabledState>,
        })
    }
}
```

Rust Embedded Tooling: Proptest + Mocking

```
#[test]
fn fuzz(mut bytes in vec(0..255u8, 9)) {
    ...
    let expectations = [
        Transaction::write(...),
        ...
    ];
    let sdp = Sdp8xx::new(I2cMock::new(&expectations), 0x10, DelayMock);
    let mut sampling = sdp.start_sampling_differential_pressure(true).unwrap();
    let _result = sampling.read_continuous_sample();
    let sdp = sampling.stop_sampling().unwrap();
    sdp.release().done();
}
```

crates.io/crates/proptest

[Example on GitHub]()

Example Project:

LoRa Module Driver

LoRa Transmitter/Receiver

LoRa: Efficient long range radio tech

Ebyte E32 Module: offer simplified interfaces to SemTech Radios

Allegedly 8Km Range with E32-433T30D, at 433MHz (ISM-Band)

Transceiver: Sender + Receiver

Product on ebyte.com

LoRa Transmitter/Receiver

github.com/barafael/ebyte-e32-rs

`#[no_std]` Driver for Ebyte E32 LoRa Modules

- Embedded Hal: Serial Peripheral + some GPIOs
- Mocking with embedded-hal-mock
- Property-Based Testing with proptest
- Mutation Testing with cargo-mutants
- Configuration in data structures

LoRa Transmitter/Receiver: Parameters

```
#[derive(Debug                                               )]

pub enum BaudRate {
    Bps1200,
    Bps2400,
    Bps4800,

    Bps9600,
    Bps19200,
    Bps38400,
    Bps57600,
    Bps115200,
}
```

LoRa Transmitter/Receiver: Parameters

```
#[derive(Debug, Copy, Clone, PartialEq, Eq, SmartDefault)]
#[cfg_attr(test, derive(proptest_derive::Arbitrary))]
#[cfg_attr(feature = "arg_enum", derive(clap::ArgEnum))]
pub enum BaudRate {
    Bps1200,
    Bps2400,
    Bps4800,
    #[default]
    Bps9600,
    Bps19200,
    Bps38400,
    Bps57600,
    Bps115200,
}
```

This code on GitHub

LoRa Transmitter/Receiver: Parameters

```
#[derive(Debug                                    )]

pub struct Parameters {
    pub address: u16,
    pub channel: u8,

    pub uart_rate: BaudRate,
    ...
}
```

LoRa Transmitter/Receiver: Parameters

```rust
#[derive(Debug, Clone, PartialEq, Eq, TypedBuilder)]
#[cfg_attr(test, derive(proptest_derive::Arbitrary))]
pub struct Parameters {
    pub address: u16,
    pub channel: u8,
    #[builder(default)]
    pub uart_rate: BaudRate,
    ...
}
```

This code on GitHub

LoRa Transmitter/Receiver: I/O

```rust
pub fn model_data(&mut self) -> Result<ModelData, Error> {
    Program::set_pins(&mut self.aux, &mut self.m0, &mut self.m1);
    let result = self.read_model_data();
    Normal::set_pins(&mut self.aux, &mut self.m0, &mut self.m1);
    result
}
```

This code on GitHub

LoRa Transmitter/Receiver: I/O

```rust
fn read_model_data(&mut self) -> Result<ModelData, Error> {
    block!(self.serial.write(0xC3)).map_err(|_| Error::SerialWrite)?;

    let save = block!(self.serial.read()).map_err(|_| Error::SerialRead)?;
    let model = block!(self.serial.read()).map_err(|_| Error::SerialRead)?;
    ...

    if save == 0xC3 {
        Ok(ModelData {
            model,
            version,
            features,
        })
    } else {
        Err(Error::ReadModelData)
    }
}
```

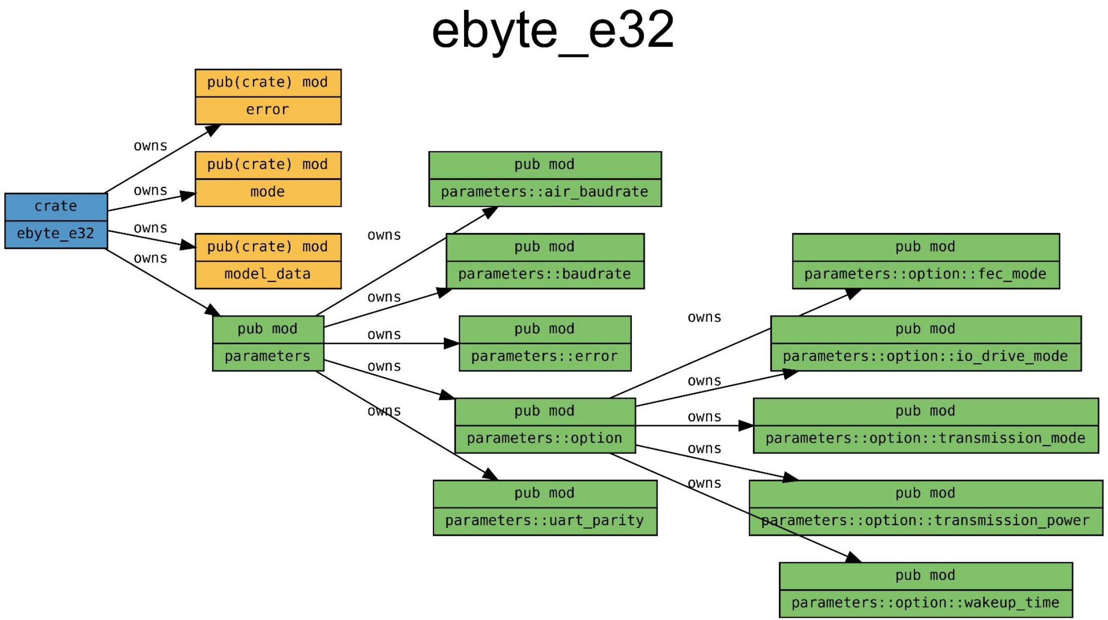
This code on GitHub

LoRa Transmitter/Receiver: Usage

```rust
let ebyte = Ebyte::new(serial, aux, m0, m1, delay).unwrap();
let mut params = ebyte.read_parameters().unwrap();

params.air_rate = AirBaudRate::Bps300;

ebyte
    .set_parameters(&params, Persistence::Temporary)
    .unwrap();

loop {
    delay_tim5.delay_ms(5000u32);
    rprintln!("Sending it!");
    ebyte.write_buffer(b"it").unwrap();
}
```

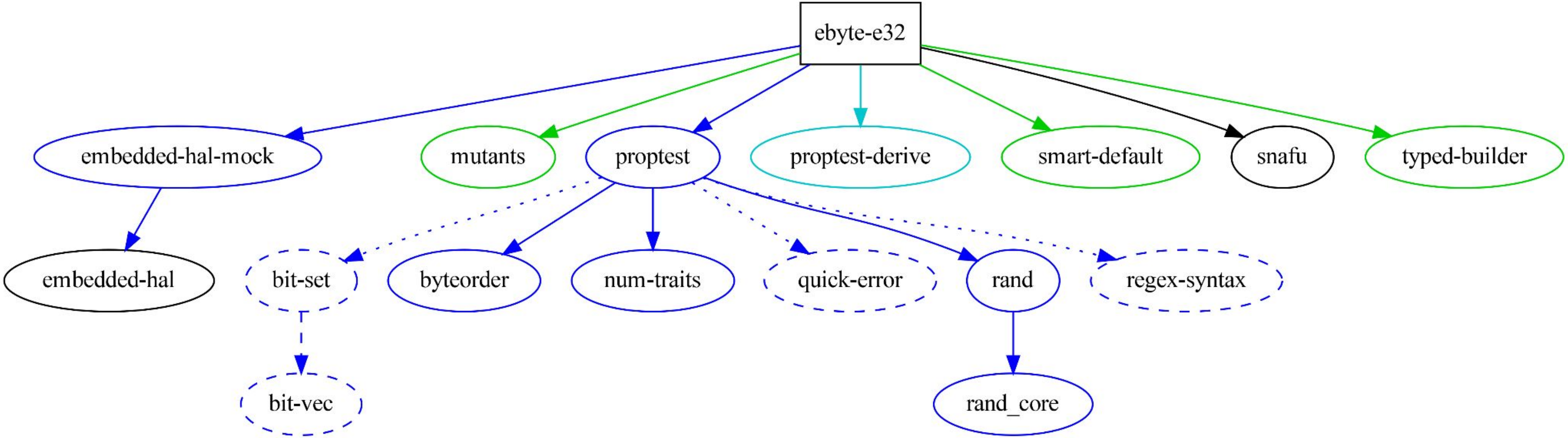
This code on GitHub

LoRa Transmitter/Receiver Module Structure



`cargo modules generate graph > mods.dot`

LoRa Transmitter/Receiver Dependencies



`cargo depgraph > deps.dot`

Raspberry Pi LoRa Transmitter/Receiver (CLI/GUI)

So many configurations. How to test this? CLI and GUI

- Declarative CLI definition via `clap`
- Generated GUI with `klask` (uses `clap`)
- Cross-Compilation für Raspberry Pi mit `cross` (Docker):

  `cross build --target armv7-unknown-linux-musleabihf`

Raspberry Pi LoRa Transmitter/Receiver (CLI)

```rust
#[derive(Debug                                        )]

pub struct App {
    /// Module Address (16 Bit).

    pub address: u16,

    /// UART Baudrate.

    pub uart_rate: BaudRate,
    ...
}
```

This code on GitHub

Raspberry Pi LoRa Transmitter/Receiver (CLI)

```
#[derive(Debug, Clone, PartialEq, Eq, clap::Parser)]
#[clap(author, version, about, long_about = None)]
pub struct App {
    /// Module Address (16 Bit).
    #[clap(short, long, required = true)]
    pub address: u16,

    /// UART Baudrate.
    #[clap(arg_enum, long, required = false, ignore_case(true))]
    pub uart_rate: BaudRate,
    ...
}
```

This code on GitHub

Raspberry Pi LoRa Transmitter/Receiver (CLI)

Fields

`address: u16`
Module Address (16 Bit).

`channel: u8`
Channel (8 Bit).

`persistence: Persistence`
Whether settings should be saved persistently on the module.

`uart_parity: Parity`
UART Parity.

`uart_rate: BaudRate`
UART Baudrate.

`air_rate: AirBaudRate`
Air Baudrate.

`transmission_mode: TransmissionMode`
Transmission Mode.

`io_drive_mode: IoDriveMode`
IO drive Mode for AUX pin.

`wakeup_time: WakeupTime`
Wireless Wakeup Time.

`fec: ForwardErrorCorrectionMode`
Forward Error Correction Mode.

`transmission_power: TransmissionPower`
Transmission Power.

Enum ebyte_e32::parameters::uart_parity::Parity

source · [-]

```
pub enum Parity {
    None,
    Odd,
    Even,
}
```

Raspberry Pi LoRa Transmitter/Receiver (CLI)

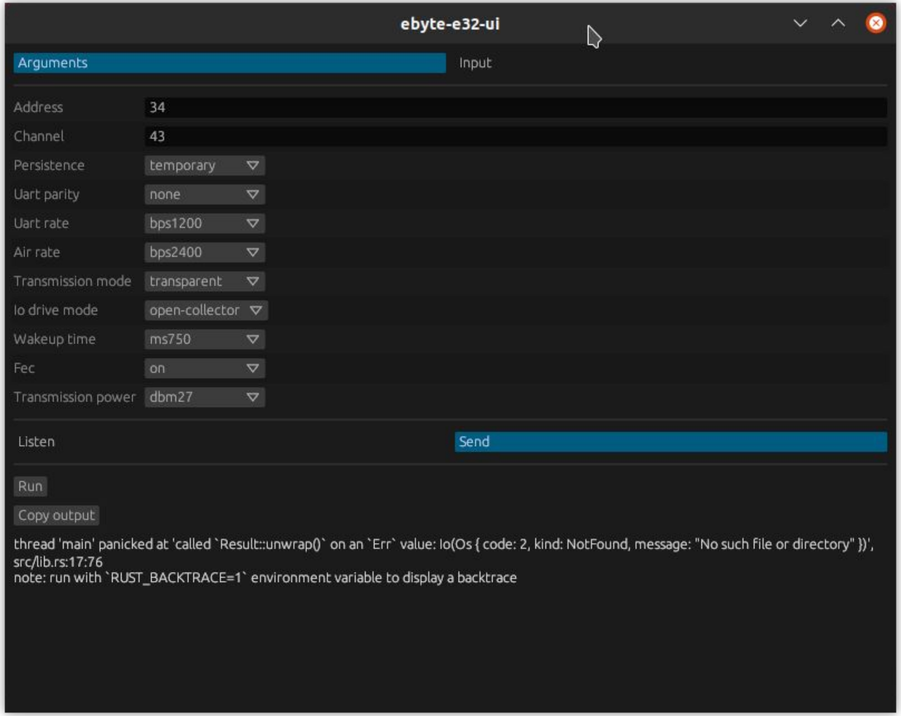
```
ebyte-e32-cli 0.1.0

USAGE:
    ebyte-e32-cli [OPTIONS] --address <ADDRESS> --channel <CHANNEL> <SUBCOMMAND>

OPTIONS:
    -a, --address <ADDRESS>
            Module Address (16 Bit)

        --air-rate <AIR_RATE>
            Air Baudrate [default: bps2400] [possible values: bps300, bps1200, bps2400, bps4800,
            bps9600, bps19200]

    -c, --channel <CHANNEL>
            Channel (8 Bit)
```

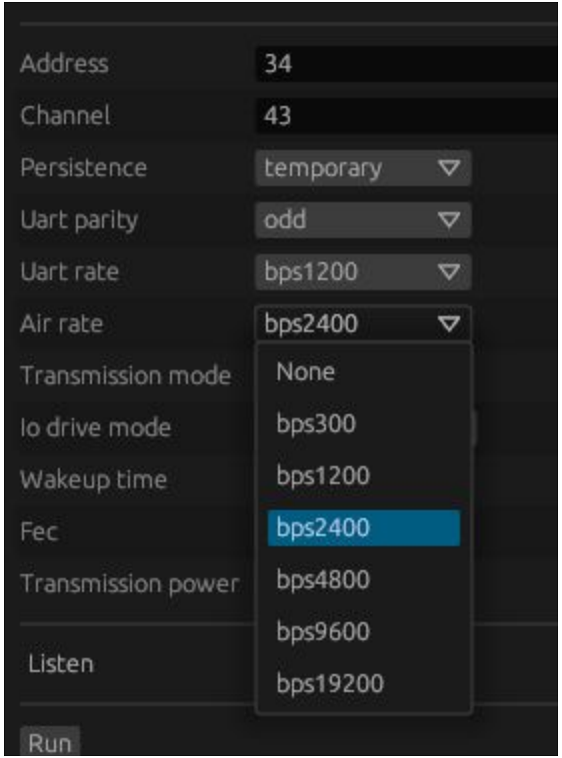
Raspberry Pi LoRa Transmitter/Receiver (GUI)

```
fn main() {
    klask::run_derived::<App, _>(Settings::default(), process);
}
```

Function `process`: [on GitHub]

Raspberry Pi LoRa Transmitter/Receiver (GUI)



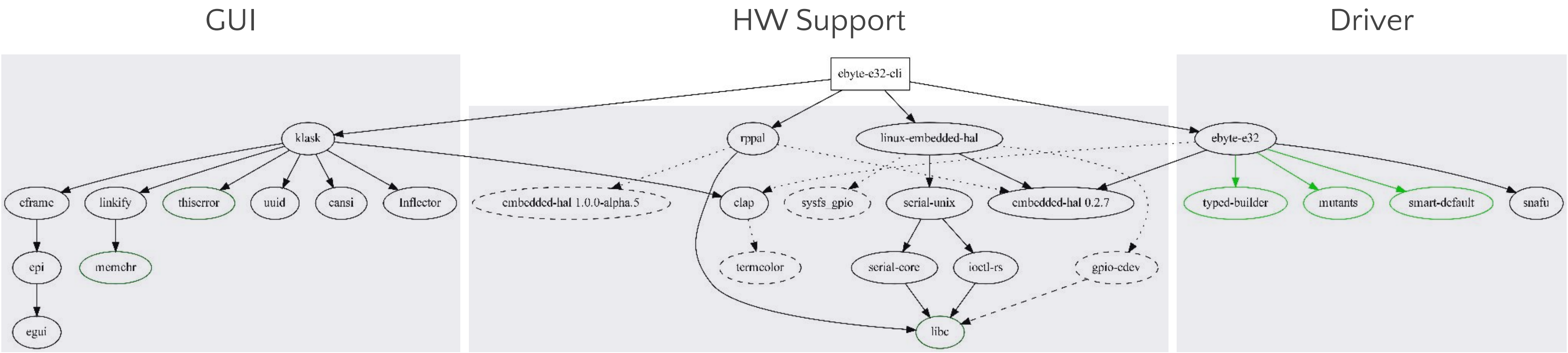


Raspberry Pi LoRa Transmitter/Receiver

cargo audit

```
 ~/ebyte-e32-ui   main *3 ?2   cargo audit
    Fetching advisory database from `https://github.com/RustSec/advisory-db.git`
      Loaded 416 security advisories (from /home/rafael/.cargo/advisory-db)
    Updating crates.io index
    Scanning Cargo.lock for vulnerabilities (228 crate dependencies)
Crate:         xcb
Version:       0.10.1
Title:         Multiple soundness issues
Date:          2021-02-04
ID:            RUSTSEC-2021-0019
URL:           https://rustsec.org/advisories/RUSTSEC-2021-0019
Solution:      Upgrade to >=1.0
Dependency tree:
xcb 0.10.1
└── x11-clipboard 0.5.3
    └── copypasta 0.7.1
        └── egui-winit 0.16.0
            ├── egui_glium 0.16.0
            │   └── eframe 0.16.0
            │       └── klask 1.0.0
            │           └── ebyte-e32-ui 0.1.0
            └── eframe 0.16.0

error: 1 vulnerability found!
```

Raspberry Pi LoRa Transmitter/Receiver (CLI/GUI)



github.com/barafael/ebyte-e32-rs

github.com/barafael/ebyte-e32-ui

RTIC:

Real-**T**ime

Interrupt-driven

Concurrency

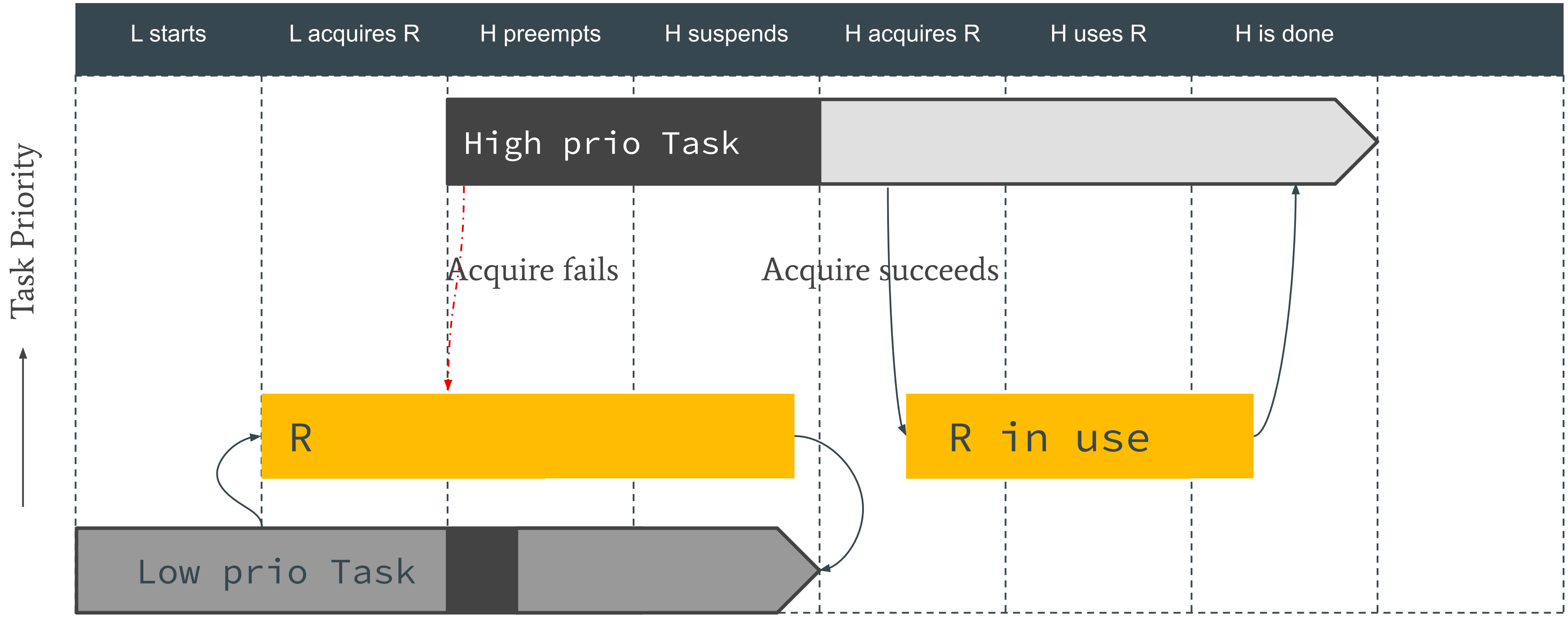
RTIC: Real-Time Interrupt-Driven Concurrency

- Framework for event driven realtime applications (but no RTOS)
- Run-to-completion tasks (just interrupt handlers)
- Software-triggered tasks, timer queue, message passing
- Preemptive Multitasking without Software Scheduler
    - ARM NVIC hardware used as scheduler
- Statically prevents deadlocks
- Statically prevents priority inversion
- **Priority Ceiling Protocol**

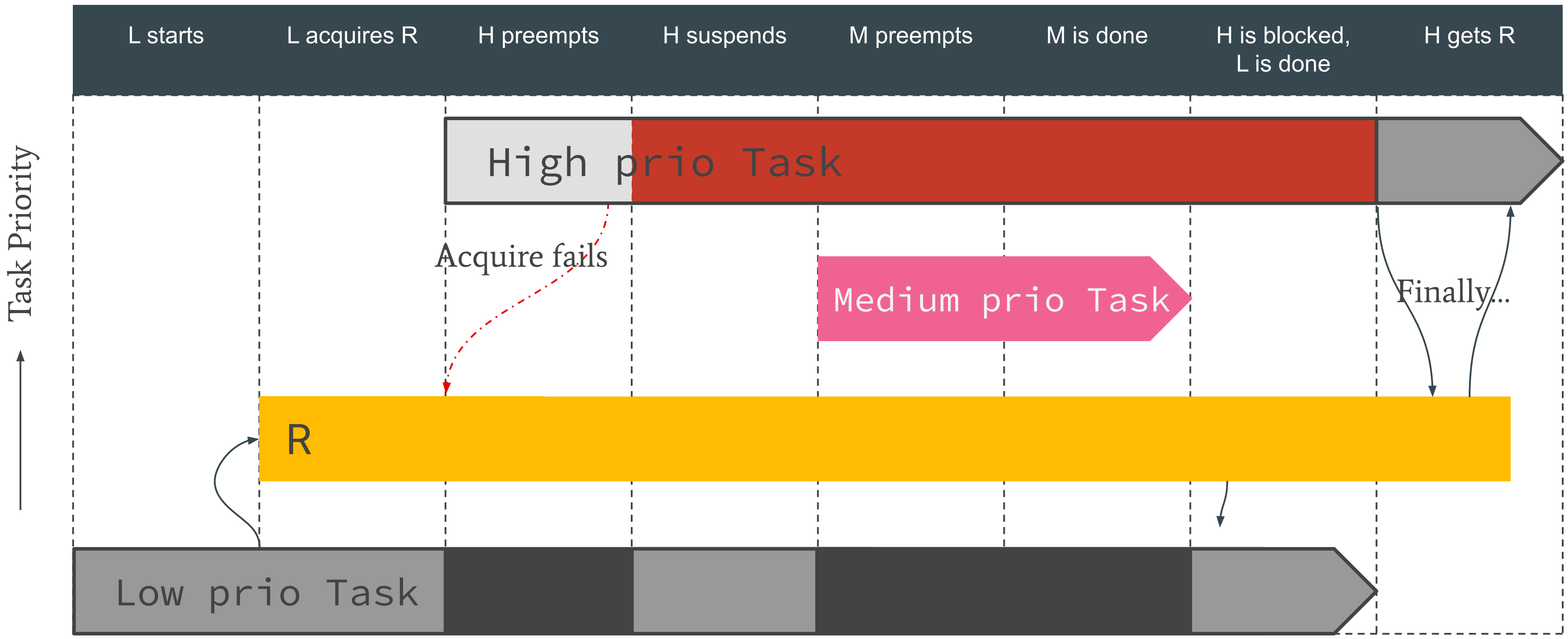
rtic.rs

minimal app

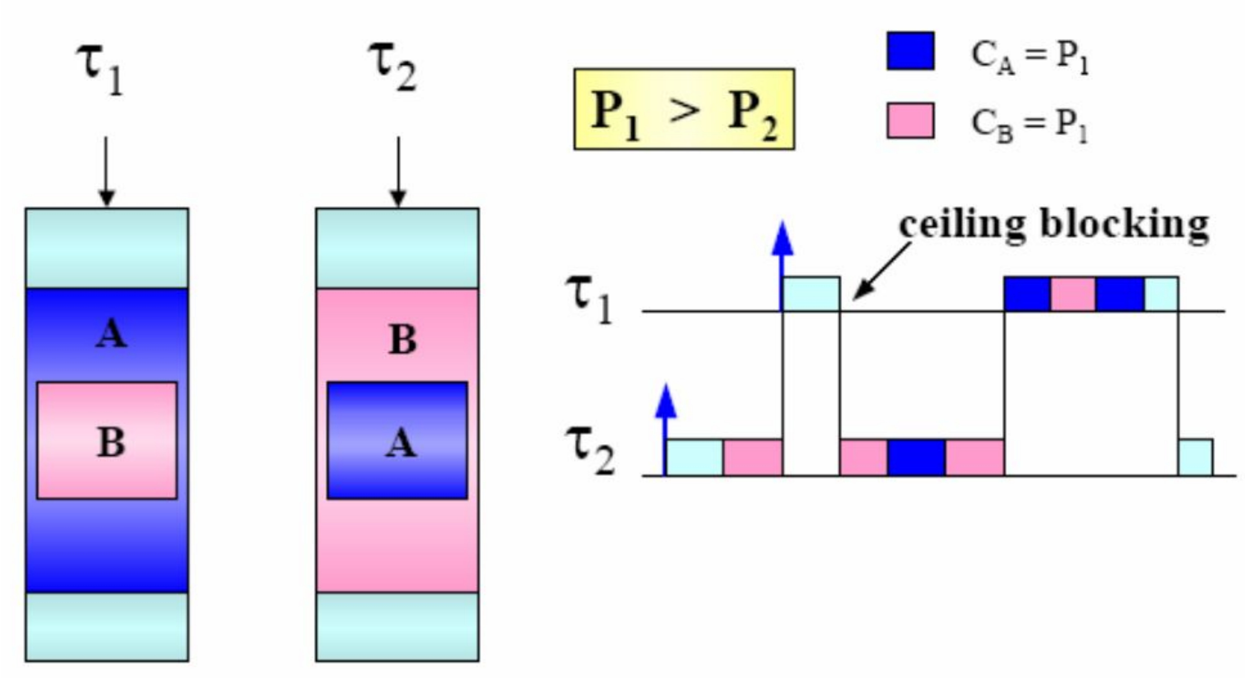
Preemptive Scheduling with Priorities (Happy Path)



Priority Inversion



Deadlock



J. Ras and A. M. K. Cheng, "An Evaluation of the Dynamic and Static Multiprocessor Priority Ceiling Protocol and the Multiprocessor Stack Resource Policy in an SMP System," 2009 15th IEEE Real-Time and Embedded Technology and Applications Symposium, 2009, pp. 13-22, doi: 10.1109/RTAS.2009.10.

RTIC: Real-time Interrupt-driven Concurrency

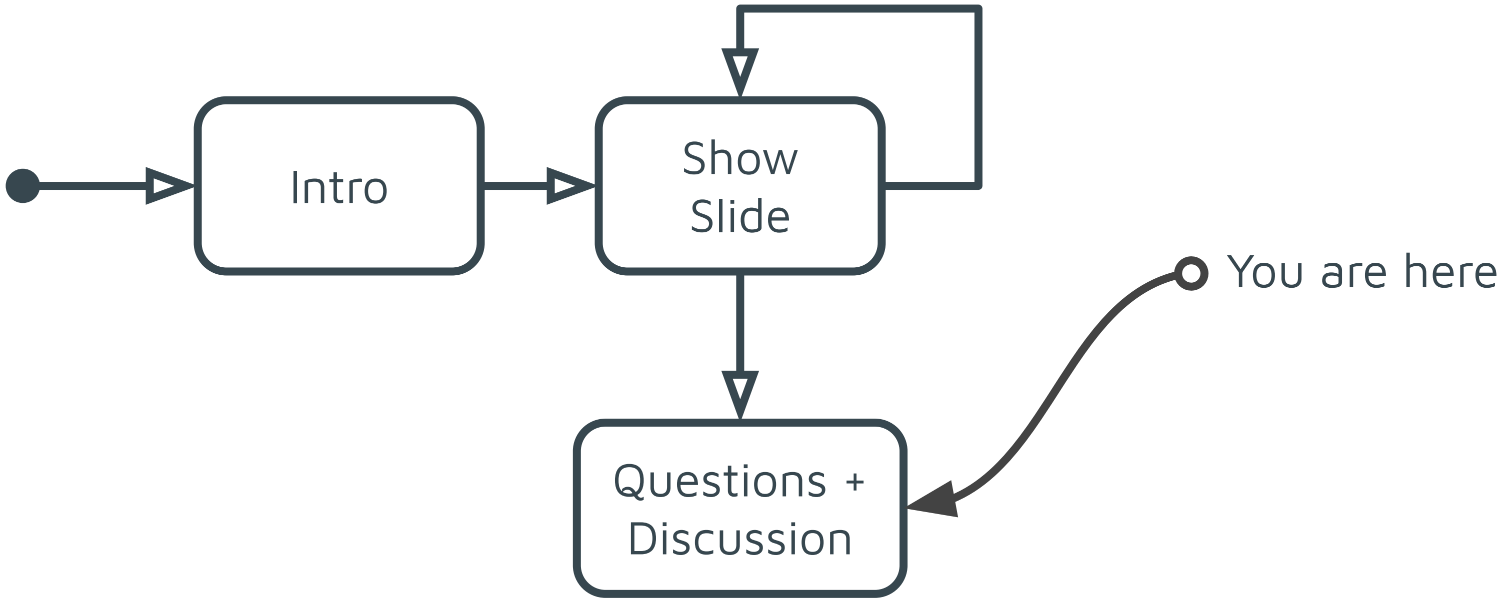
- Priority Ceiling Protocol
  - Task A locks Ressource => A gets temporary higher priority P
  - P chosen such that: other tasks using the same resource cannot spawn (A cannot be preempted by them)
  - One single WRITE on **BASEPRI** suffices

- PCP prevents:
  - Priority inversion (medium prio task cannot preempt)
  - Deadlock (higher priority task cannot preempt)

RTIC Beispiel

```rust
// In Setup:
pin.make_interrupt_source(&mut sys_cfg);
pin.enable_interrupt(&mut ctx.device.EXTI);
pin.trigger_on_edge(&mut ctx.device.EXTI, Edge::Falling);

blink::spawn().ok();

// Task:
#[task(binds = EXTI0, local = [pin])]
fn on_exti(ctx: on_exti::Context) {
    ctx.local.pin.clear_interrupt_pending_bit();
    rprintln!("incrementing");
    COUNTER.fetch_add(1, Ordering::SeqCst);
}
```

Many examples on GitHub


Intro
Show Slide
Questions + Discussion
You are here