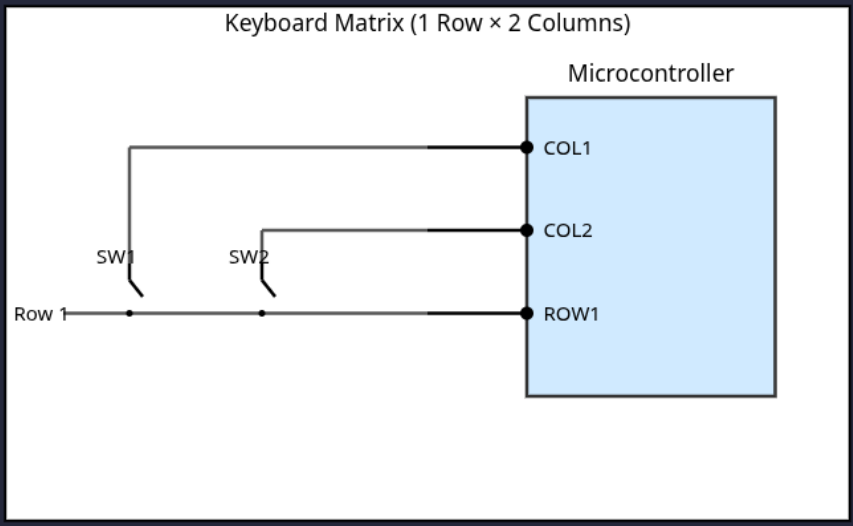
Async Rust on bare metal with Embassy

Prabhpreet Dua

Hello hardware: Let us build a contrived embedded system



How it should work:

- Column voltages alternately toggle every 100 ms
- Row is read if column is connected

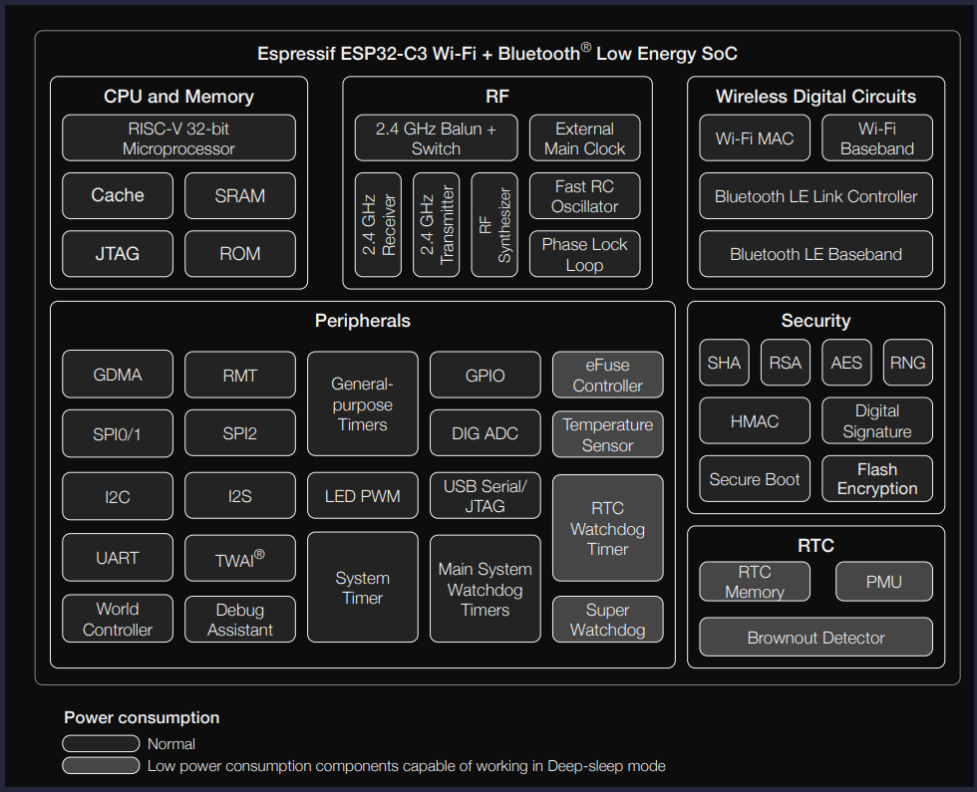
Let's build some (horrible) firmware

Embedded Systems: The Brains

Microcontrollers: processor(s) + peripherals

ESP32C3

~ 408K SRAM, 4MB on-board flash



Concurrency on embedded systems

Patterns:

- Superloop: KISS- implement state machine
- Superloop(ish) with interrupts
- Real time operating systems:
  - Task, scheduling algorithms, context switches
    - FreeRTOS
    - RT Linux
    - VxWorks
- async/await: A new paradigm?

	Superloop	RTOS	async/await
Blocking OK?	No	Yes	No
Scheduling	Cooperative	Preemptive	Cooperative
User Interface	State Machines	Normal/Procedural	Normal/Procedural
Stack	One	One per task	One
Event Loop (UX)	One	One per task	One per task

Embassy

> "An executor AND a Hardware Access Layer (HAL)" framework

Executor

- No alloc, no heap needed.
- Statically allocated tasks
- No busy-loop polling: CPU sleeps using interrupts or WFE/SEV.
- Efficient polling: a wake will only poll the woken task, not all of them.
- Fair task scheduling

HAL

- Batteries Included: Networking, Bluetooth, USB ...
- esp-embassy-hal: Has it's own executor wrapper, timer driver

KB Implementation in Embassy

```
bash goto.sh async-impl-v1 asynckb-esp/src/bin/main.rs 1
```

──────────────────────── [finished] ────────────────────────

Three tasks

main

- Initializes, stores input/output "drivers" in static memory
- Spawns other 2 tasks
- Receives PrintEvent to print output (think communication process)

process_input_task

- Asynchronously waits for an input edge trigger
- Detects if high/low to track if button is pressed, and current column through atomic load
- Sends PrintEvent through Channel

output_toggle_task

- Waits for matrix poll time: 100ms
- Toggles output
- Stores current pin index in atomic

Demo

KB Implementation in Embassy

Emulation, tracing

```
bash goto.sh async-impl-v1 asynckb-spin/src/main.rs 1
```

──────────────────────── [finished] ────────────────────────

- On arch-spin target emulation
- Perfetto traces using tracing-subscriber: ui.perfetto.dev

KB Implementation in Embassy

Macros Expanded

```
bash goto.sh async-impl-v1m asynckb-spin/src/main.rs 1
```

──────────────────────── [finished] ────────────────────────

Wrapper

- Original main and task functions are renamed
- Wrapped with `fn(args) -> SpawnToken<impl Sized>`

Entrypoint

Main function creates an executor, transmutes its lifetime to static and executes `run` method on it

Walkthrough with memory view

Entrypoint

```
bash goto.sh async-impl-v1m asynckb-spin/src/main.rs 68
```

[finished]

Walkthrough with memory view

Entrypoint

- Executor created on stack

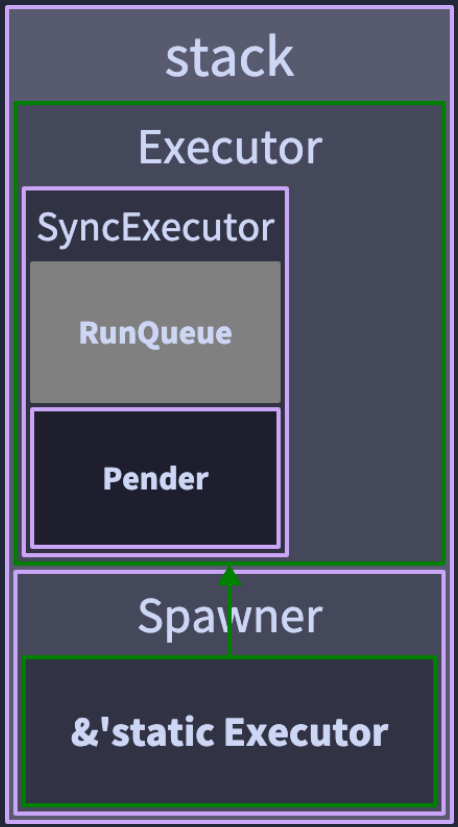
Observations:

- Executor created, and transmutes lifetime to static
- SpinExecutor and raw::Executor are non-send, non-sync, despite holding SyncExecutor

Walkthrough with memory view

Executor runs

- Executor gets a spawner



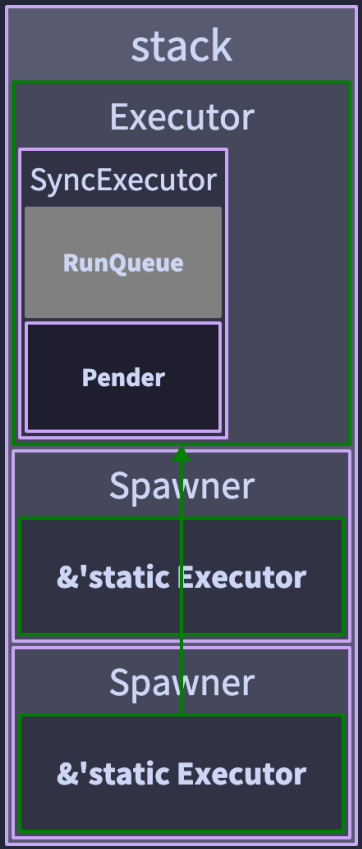
Observations:

- Spawner is not-send, and copy

Walkthrough with memory view

Executor runs

- Executor runs the init closure: `FnOnce(Spawner)`
- Generate spawn token: `fn task_spawner(args) -> SpawnToken<impl Sized>`

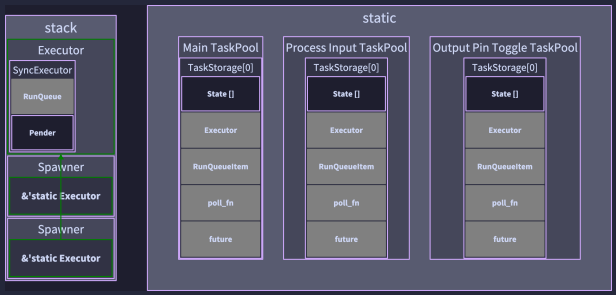


Observations: Copy the spawner in the task spawner

Walkthrough with memory view

Executor runs: Generating Spawn Token

- New TaskPool



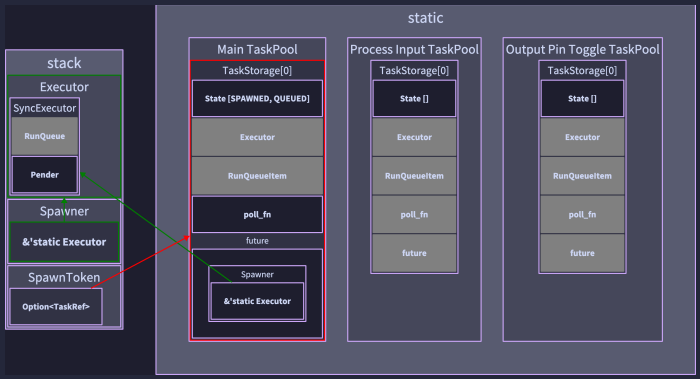
Observations:

- Static initialization of TaskPool (bss)
- TaskPoolHolder holds data size of pool with alignment, transmute from TaskPool

Walkthrough with memory view

Executor runs: Generating Spawn Token

- Spawn async fn



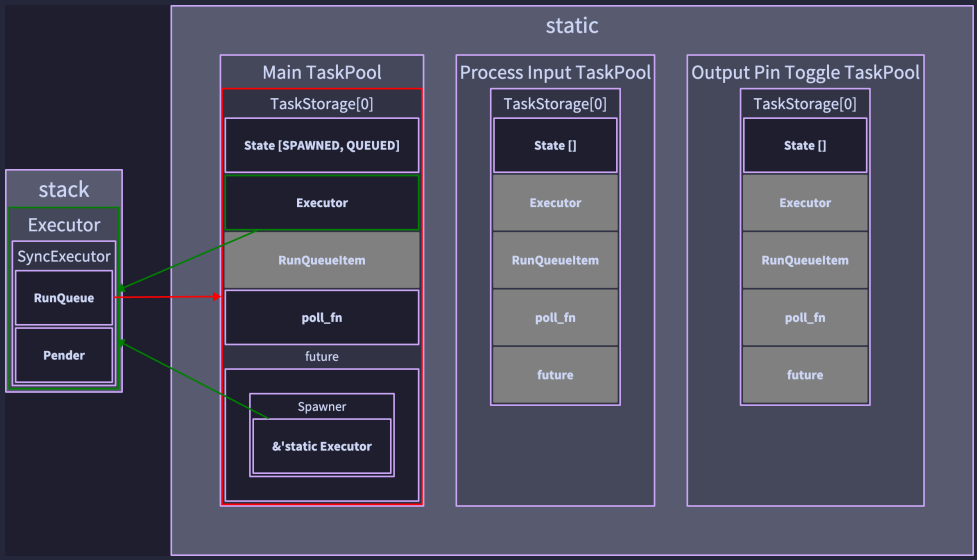
Observations:

- Task init state initialized
  - Moved Spawner copy and generated future
  - Reserved task storage in task pool
  - Generated a spawn token
- Spawn Token generic monomorphised on Future Type

Walkthrough with memory view

Executor runs: Must Spawn

- `spawner.must_spawn<S>(token: SpawnToken<S>)`
- Consumes spawn token



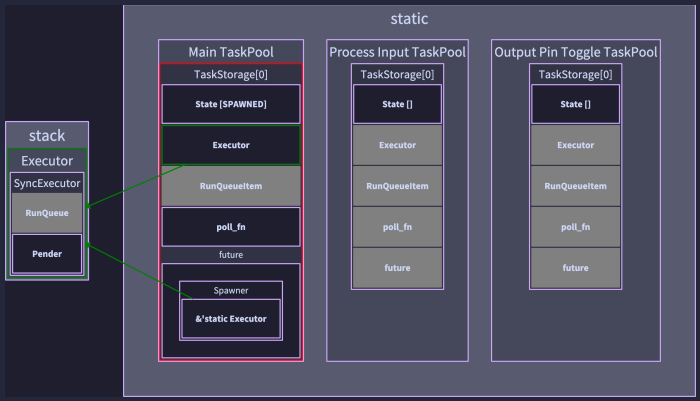
Observations:

- Spawn token consumed without drop
- Task enqueued with executor runqueue, and pender "pended"
- Fails on a bad spawn token

Walkthrough with memory view

Executor runs: finally!

- Polling starts
- Run queue dequeues every task



Observations:

- TaskStorage state cleared the QUEUED flag

Walkthrough with memory view

Executor runs: finally!

- Polling starts
- Run queue dequeues every task
- Polling main task future

Poll function:

```
bash goto.sh async-impl-v1m embassy/embassy-executor/src/raw/mod.rs
230
```

[finished]

Mask off: A recap of Future

```rust
pub trait Future {
  type Output;

  fn poll(self: Pin<&mut Self>, cx: &mut
Context<'_>) -> Poll<Self::Output>;
}

pub enum Poll<T> {
  Ready(T),
  Pending,
}

pub struct Context<'a> { /* private fields */
}
impl<'a> Context {
  pub const fn waker(&self) -> &'a Waker;
}

pub struct Waker { /* private fields */ }
impl Waker {
    pub fn wake(self);
}
```

Running futures

Executor

Poll the futures, but don't poll pending ones, unless they are woken up through a Waker

Reactor

Invoke wakers

A recap of Future

Waking mechanism

```
pub const unsafe fn Waker::new(
    data: *const (),
    vtable: &'static RawWakerVTable) -> Waker;

/// A virtual function pointer table (vtable) that specifies the
behavior of a RawWaker.
/// The pointer passed to all functions inside the vtable is the
data pointer from the enclosing RawWaker object.

pub const fn RawWakerVTable::new(
    clone: unsafe fn(*const ()) -> RawWaker,
    wake: unsafe fn(*const ()),
    wake_by_ref: unsafe fn(*const ()),
    drop: unsafe fn(*const ()),
) -> RawWakerVTable
```

Embassy Waker

Just a TaskRef

```
bash goto.sh async-impl-v1m
embassy/embassy-executor/src/raw/waker.rs 1
```

[finished]

Observations

On wake, the waker does two things:

- Sets back QUEUED state for the task
- Enqueues task by swapping executor RunQueue with its TaskRef and setting its RunQueueItem as the swapped TaskRef

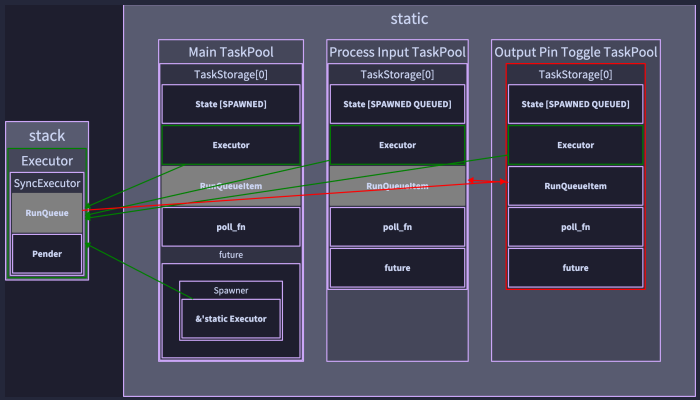
Walkthrough with memory view

Executor runs: finally!

- Polling starts
- Run queue dequeues every task
- Polling main task future- init, spawn two other tasks

```
bash goto.sh async-impl-v1m asynckb-spin/src/main.rs 24
```

```
──────────────────────────── [finished] ────────────────────────────
```



Observations:

- Two spawned tasks enqueued, and pender pended
- Wakers created from task
- Main Task is dequeued until receiver waker is woken

Walkthrough with memory view

The next poll

- Process input & output pin toggle tasks remin in queue
- Poll loop starts again: dequeue tasks, and poll them for the first time

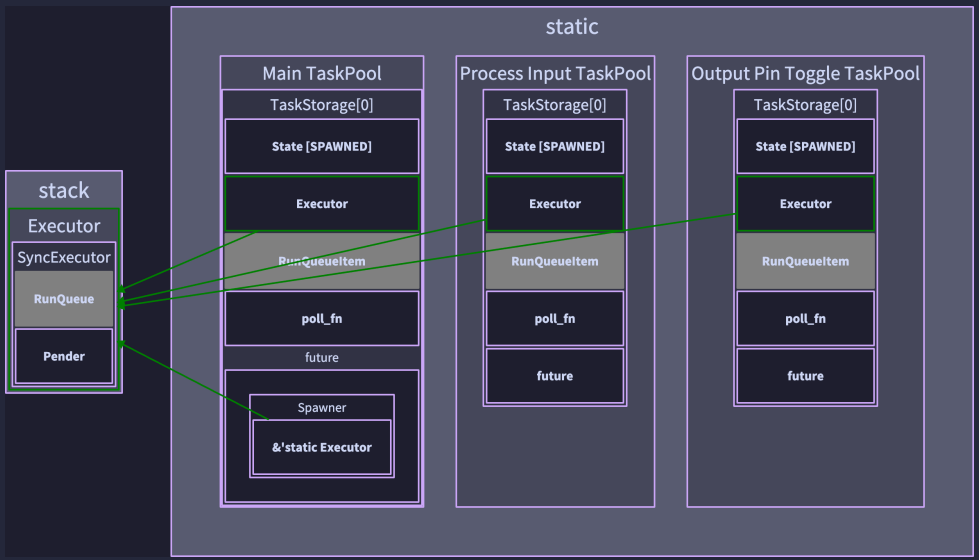
Process Input

Will register its waker with GPIO interrupt driver/handlers

Output pin toggle

Toggle output, and register its waker with embassy timer driver

Aftermath



Embassy Timer

- Embassy Timer crate: `Timer`, `Instant` types
- Embassy time driver: one global driver to rule them all

Timer crate

```rust
pub struct Instant {
    ticks: u64,
}

pub struct Timer {
    expires_at: Instant,
    yielded_once: bool,
}

impl Future for Timer {
    type Output = ();
    fn poll(mut self: Pin<&mut Self>, cx: &mut Context<'_>) ->
Poll<Self::Output> {
        if self.yielded_once && self.expires_at <= Instant::now() {
            Poll::Ready(())
        } else {
            embassy_time_driver::schedule_wake(self.expires_at.
as_ticks(), cx.waker());
            self.yielded_once = true;
            Poll::Pending
        }
    }
}
```

Embassy Timer

embassy_time_driver

```rust
pub trait Driver: Send + Sync + 'static {
    fn now(&self) -> u64;
    fn schedule_wake(&self, at: u64, waker: &Waker);
}

extern "Rust" {
    fn _embassy_time_now() -> u64;
    fn _embassy_time_schedule_wake(at: u64, waker: &Waker);
}

pub fn now() -> u64 {
    unsafe { _embassy_time_now() }
}

pub fn schedule_wake(at: u64, waker: &Waker) {
    unsafe { _embassy_time_schedule_wake(at, waker) }
}
```

Embassy Timer

embassy_time_driver

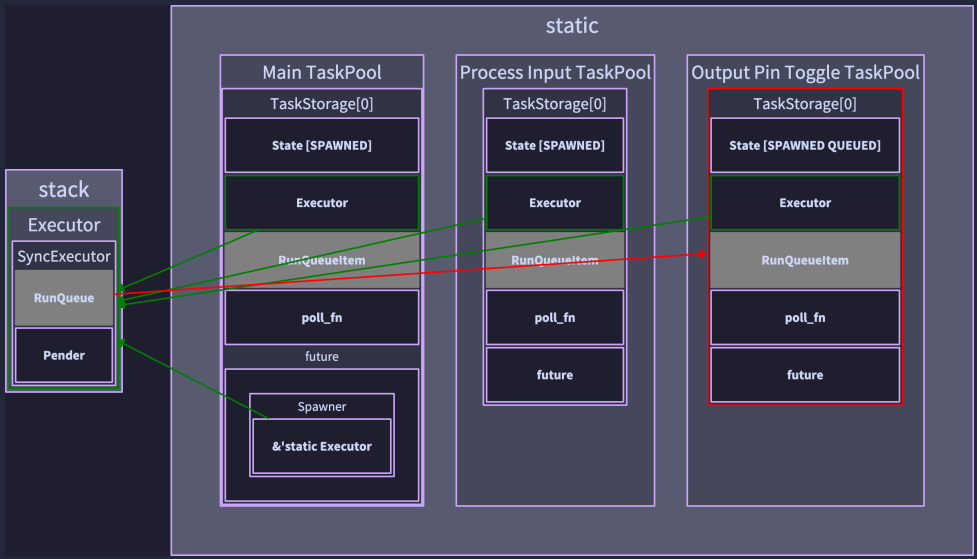
```
#[macro_export]
macro_rules! time_driver_impl {
    (static $name:ident: $t: ty = $val:expr) => {
        static $name: $t = $val;

        #[no_mangle]
        fn _embassy_time_now() -> u64 {
            <$t as $crate::Driver>::now(&$name)
        }

        #[no_mangle]
        fn _embassy_time_schedule_wake(at: u64, waker:
&core::task::Waker) {
            <$t as $crate::Driver>::schedule_wake(&$name, at,
waker);
        }
    };
}
```

100ms later: timer waker invoked, and no inputs trigerred

Recall

On wake, the waker does two things:

- Sets back QUEUED state for the task
- Enqueues task by swapping executor RunQueue with its TaskRef and setting its RunQueueItem as the swapped TaskRef



Similar pattern on-and-on

ESP Embassy HAL internals

Executor

```
bash goto.sh async-impl-v1m
esp-hal/esp-hal-embassy/src/executor/thread.rs 158
```

[finished]

ESP Embassy HAL internals

Pender HAL implementation

Specify executor core as context

```
bash goto.sh async-impl-v1m
esp-hal/esp-hal-embassy/src/executor/mod.rs 11
```

[finished]

RISC V WFI instruction

3.2.3 Wait for Interrupt

The Wait for Interrupt instruction (WFI) provides a hint to the implementation that the current hart can be stalled until an interrupt might need servicing. Execution of the WFI instruction can also be used to inform the hardware platform that suitable interrupts should preferentially be routed to this hart. WFI is available in all of the supported S and M privilege modes, and optionally available to U-mode for implementations that support U-mode interrupts.

31 — 20	19 — 15	14 — 12	11 — 7	6 — 0
funct12	rs1	funct3	rd	opcode
12	5	3	5	7
WFI	0	PRIV	0	SYSTEM

If an enabled interrupt is present or later becomes present while the hart is stalled, the interrupt exception will be taken on the following instruction, i.e., execution resumes in the trap handler and `mepc` = `pc` + 4.

The following instruction takes the interrupt exception and trap, so that a simple return from the trap handler will execute code after the WFI instruction.

The WFI instruction is just a hint, and a legal implementation is to implement WFI as a NOP.

If the implementation does not stall the hart on execution of the instruction, then the interrupt will be taken on some instruction in the idle loop containing the WFI, and on a simple return from the handler, the idle loop will resume execution.

We have removed the earlier requirement that implementations ignore the rs1 *and* rd *fields, so non-zero values in these fields should now raise illegal instruction exceptions.*

ESP Embassy HAL internals

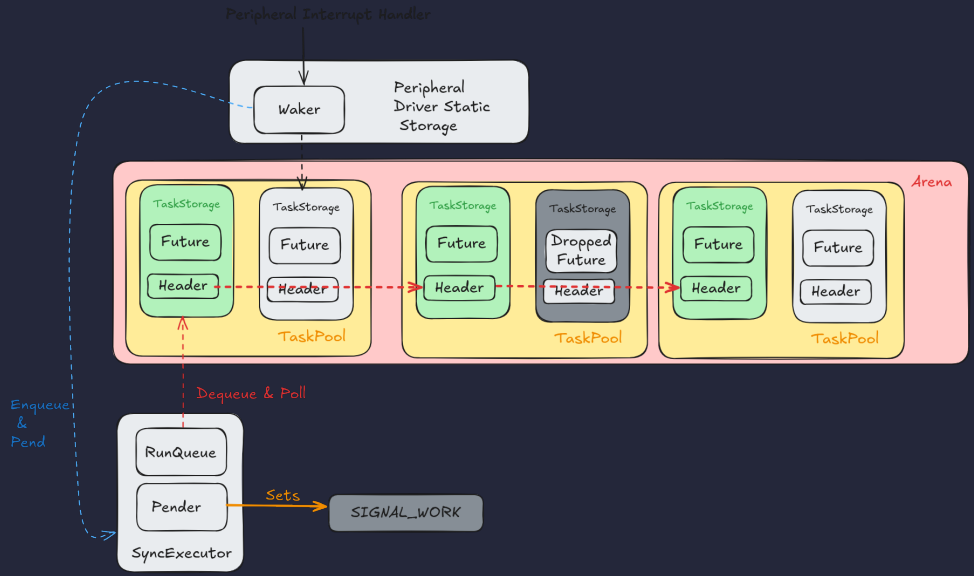
GPIO

An interrupt handler with static list of wakers for each GPIO pin (AtomicWakers)

```
bash goto.sh async-impl-v1m esp-hal/esp-hal/src/gpio/interrupt.rs
178
```

[finished]

ESP Embassy HAL internals: Summary



References

Content is sourced from a lot of very good resources:

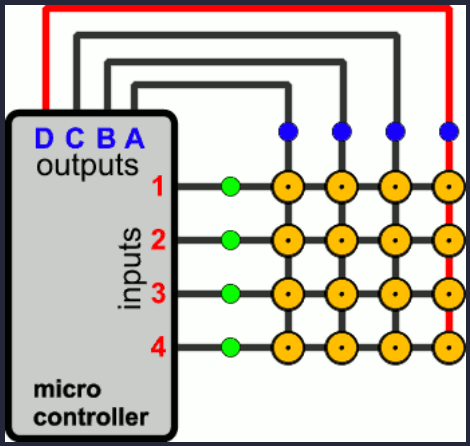
- Embedded Rust Book (https://docs.rust-embedded.org/book/intro/no-std.html)
- Rusty Bits Youtube
- Expressif Rust Book (https://docs.espressif.com/projects/rust/book/)

Archive Slides

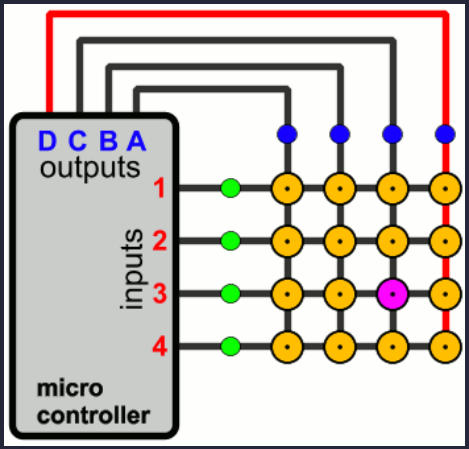
Slides from last half of presentation in July 2025

Inspiration

Keyboard Electronics Refresher



Keyboard Electronics Refresher



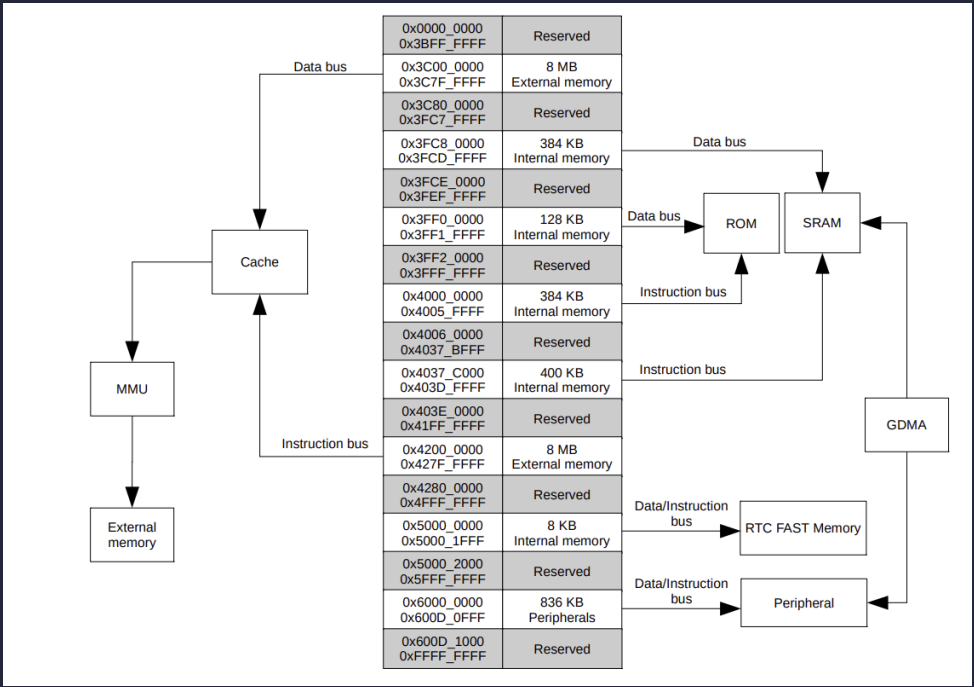
Embedded Systems: The Limbs

Peripheral access through configuring registers

We will use:

- General Purpose IO: 1 Input and 2 Outputs
- A System Timer (systimer): Read time off the timer

Configuration Registers are memory mapped



Embedded Systems and Rust

✅ no_std

🟪 entry point?

```
#[no_main]
```

ROM bootloader @ reset vector -> second stage bootloader -> application entry_point

- ROM Bootloader: setups up architecture specific registers, bootloader mode (serial)
- Second stage bootloader: Loads application, sets up memory

```
bash goto.sh sync-template-starter synckb/src/bin/main.rs 22
```

```
──────────────────────────── [finished] ────────────────────────────
```

Embedded Systems and Rust

no_std

high high hopes: panic handler

- std has unwind, and abort panic handlers
- panic halt
- panic semihosting (arm)
- define your own

```
bash goto.sh sync-template-starter synckb/src/bin/main.rs 12
```

```
──────────────────────────── [finished] ────────────────────────────
```

Embedded Systems and Rust

no_std

allocator?

- no allocator
- specify allocator with global_allocator (alloc::core)

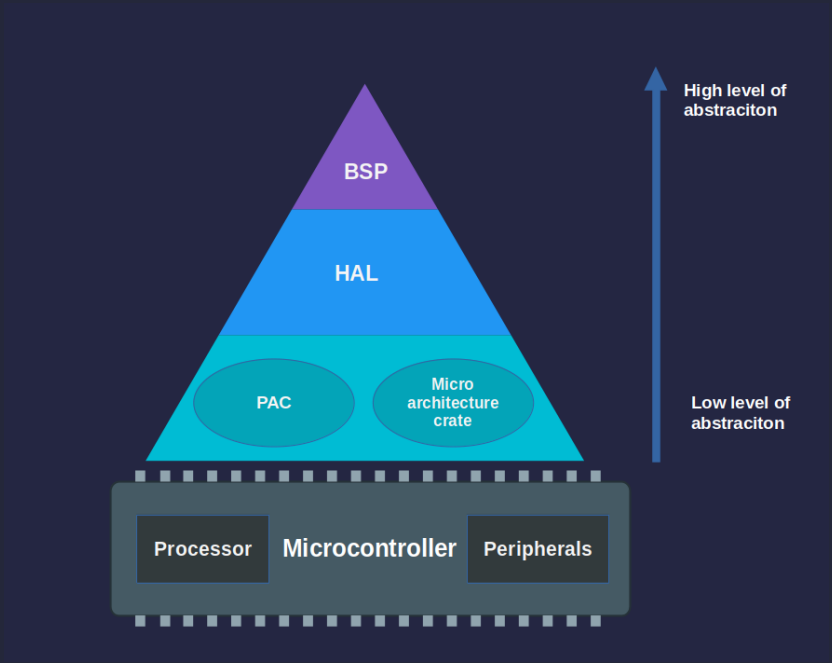
```
./goto.sh sync-template-starter synckb/src/bin/main.rs 30
```

```
──────────────────── [finished with error] ────────────────────
```

```
/var/folders/jr/gxf306790dz3zw5byfw7wyrw0000gn/T/.presentermXTuKr2/
script.sh: line 1: ./goto.sh: Permission denied
```

Embedded Systems and Rust

Developer Ecosystem



- Micro architectures: AVR, PIC, ARM Cortex, RISC V
- SoC "series": Atmel (Atmega), STM, TI (MSP), Nordic (nRF), Expressif (esp32)
- Boards & Board Support Package Config tools: SDK configs, Yocto, Buildroot, Zephyr devicetrees

Embedded Systems and Rust

PAC & HAL

- PAC: register access, singleton to manage "safe" access
- HAL:
  - Implement shared traits for reuse: `embedded-hal`, `embedded_io`
  - Think device drivers
  - init(): cpu clock, watchdog, peripheral, clocks for other peripherals

```
bash goto.sh sync-template-starter synckb/src/bin/main.rs 28
```

```
──────────────────────────── [finished] ────────────────────────────
```

basic implementation

```
bash goto.sh sync-superloop synckb/src/bin/main.rs 28
```

```
──────────────────────── [finished] ────────────────────────
```

Embedded Systems and Rust

What we did was called the superloop pattern

Let's leverage hardware to make things more power efficient

It's a trap! Exceptions & Interrupts

> We use the term exception to refer to an unusual condition occurring at run time associated with an instruction in the current RISC-V hart. We use the term interrupt to refer to an external asynchronous event that may cause a RISC-V hart to experience an unexpected transfer of control. We use the term trap to refer to the transfer of control to a trap handler caused by either an exception or an interrupt.

Interrupts

Vector Table: 31 interrupts, 15 levels of priority, level/edge triggered

ID	Address	ID	Address	ID	Address	ID	Address
0	NA	8	mtvec + 0x20	16	mtvec + 0x40	24	mtvec + 0x60
1	mtvec + 0x04	9	mtvec + 0x24	17	mtvec + 0x44	25	mtvec + 0x64
2	mtvec + 0x08	10	mtvec + 0x28	18	mtvec + 0x48	26	mtvec + 0x68
3	mtvec + 0x0c	11	mtvec + 0x2c	19	mtvec + 0x4c	27	mtvec + 0x6c
4	mtvec + 0x10	12	mtvec + 0x30	20	mtvec + 0x50	28	mtvec + 0x70
5	mtvec + 0x14	13	mtvec + 0x34	21	mtvec + 0x54	29	mtvec + 0x74
6	mtvec + 0x18	14	mtvec + 0x38	22	mtvec + 0x58	30	mtvec + 0x78
7	mtvec + 0x1c	15	mtvec + 0x3c	23	mtvec + 0x5c	31	mtvec + 0x7c

ESP32C3 Interrupt Matrix

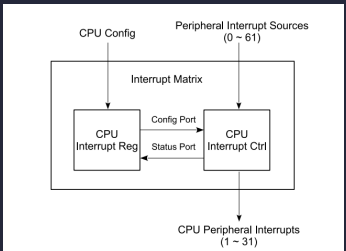


Figure 8.2-1. Interrupt Matrix Structure

Embedded Systems and Rust

critical_section

Usage:

```
static V: Mutex<Cell<u32>> = Mutex::new(Cell::new(0));

critical_section::with(|cs| { V.borrow(cs).set(42); });
```

HAL Implementation:

```
struct MyCriticalSection;
critical_section::set_impl!(MyCriticalSection);

impl unsafe critical_section::Impl for MyCriticalSection {
    unsafe fn acquire() -> RawRestoreState { ... }
    unsafe fn release(restore_state: RawRestoreState) { ... }
}

----
extern "Rust" {
    fn __acquire() -> RawRestoreState;
    fn __release(restore_state: RawRestoreState);
}
```

Embedded Systems and Rust

heapless

Fixed capacity types, for static (or stack/heap if needed)

MPMC lockfree queue

```
pub struct MpMcQueue<T, const N: usize> { /* private fields */ }

impl<T, const N: usize> MpMcQueue<T, N> {
    pub const fn new() -> Self
    pub fn dequeue(&self) -> Option<T>
    pub fn enqueue(&self, item: T) -> Result<(), T>
}
```

Embedded Systems and Rust

```
bash goto.sh superloopish-int synckb/src/bin/main.rs 103
```

```
──────────────────────── [finished] ────────────────────────
```

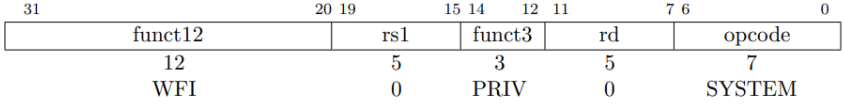
```rust
enum Event {
    KeyPress,
    KeyRelease,
}

struct TimerInterruptCtx<'a> {
    outputs: [Output<'a>; 2],
    timer: PeriodicTimer<'a, esp_hal::Blocking>,
    current_output_idx: usize,
}

static INPUT: Mutex<RefCell<Option<Input>>>;
static QUEUE:MpMcQueue<Event, 4>;

// Context needed for timer interrupt
static TIMER_INT_CTX: Mutex<RefCell<Option<TimerInterruptCtx>>>;
```

How is this more power efficient?

RISC V WFI instruction

3.2.3 Wait for Interrupt

The Wait for Interrupt instruction (WFI) provides a hint to the implementation that the current hart can be stalled until an interrupt might need servicing. Execution of the WFI instruction can also be used to inform the hardware platform that suitable interrupts should preferentially be routed to this hart. WFI is available in all of the supported S and M privilege modes, and optionally available to U-mode for implementations that support U-mode interrupts.



31 — 20	19 — 15	14 — 12	11 — 7	6 — 0
funct12	rs1	funct3	rd	opcode
12	5	3	5	7
WFI	0	PRIV	0	SYSTEM

If an enabled interrupt is present or later becomes present while the hart is stalled, the interrupt exception will be taken on the following instruction, i.e., execution resumes in the trap handler and `mepc` = `pc` + 4.

The following instruction takes the interrupt exception and trap, so that a simple return from the trap handler will execute code after the WFI instruction.

The WFI instruction is just a hint, and a legal implementation is to implement WFI as a NOP.

If the implementation does not stall the hart on execution of the instruction, then the interrupt will be taken on some instruction in the idle loop containing the WFI, and on a simple return from the handler, the idle loop will resume execution.

We have removed the earlier requirement that implementations ignore the rs1 *and* rd *fields, so non-zero values in these fields should now raise illegal instruction exceptions.*

```
bash goto.sh superloopish-int-wfi synckb/src/bin/main.rs 103
```

[finished]