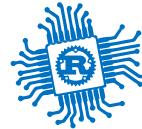


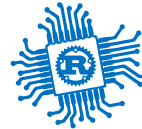
Asynchronous Development

Lecture 4



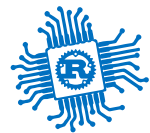
Asynchronous Development

- Concurrency
- Asynchronous Executor
- Future s
- Communication between tasks



Concurrency

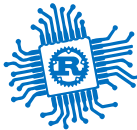
Preemptive and Cooperative



Bibliography

for this section

Brad Solomon, *Async IO in Python: A Complete Walkthrough*

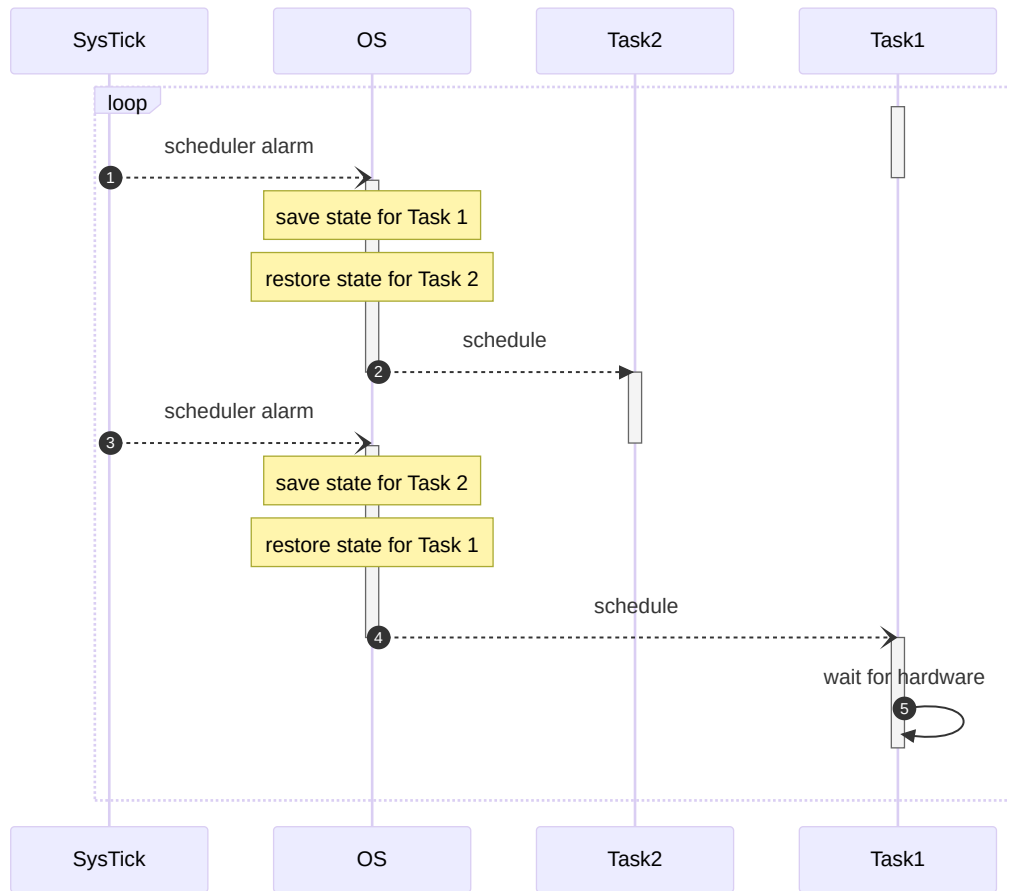


Preemptive Concurrency

- MCUs are usually *single core*^[1]
- Tasks in parallel require an OS^[2]
- Tasks can be suspended at any time
- **Switching** the task is **expensive**
- Tasks that do a lot of I/O which makes the **switching time longer than** the actual **processing time**

1. RP2350 is a dual core MCU, we use only one core ←

2. Running in an ISR is not considered a normal task ←

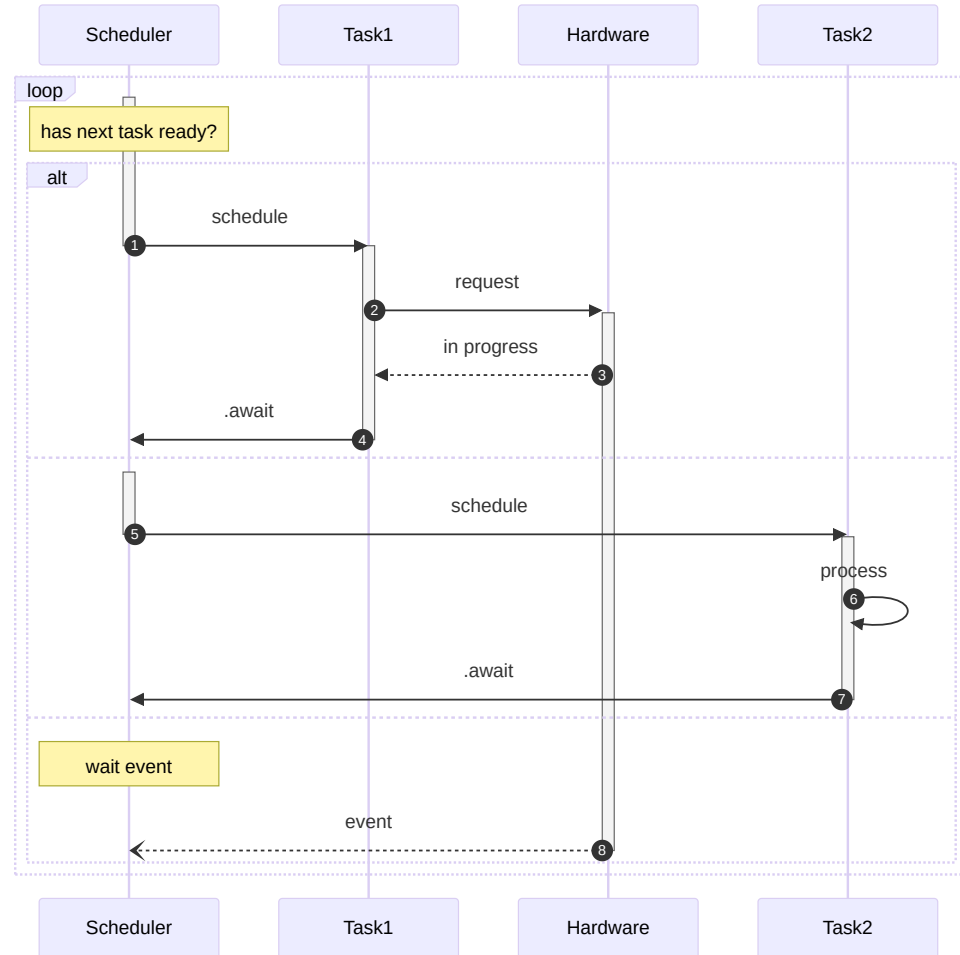


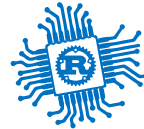


Cooperative Concurrency

- tasks cannot be interrupted^[1]
- **hardware** works in an **asynchronous** way
- tasks cooperate
 - give up the MCU for other tasks to use it while they wait for hardware
- there is **no need for an OS**, everything is done in **one single flow**
- **no penalty** for saving and restoring the state

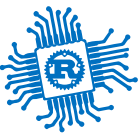
1. except for ISR ↔





Asynchronous Executor

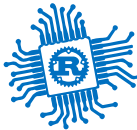
of Embassy



Bibliography

for this section

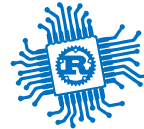
Embassy Documentation, *Embassy executor*



Tasks

- `#[embassy_executor::main]`
 - starts the Embassy scheduler
 - defines the `main` task
- `#[embassy_executor::task]` - defines a new task
 - `pool_size` - is *optional* and defines how many identical tasks can be spawned
- the `main` task
 - initializes the `led`
 - spawns the `led_blink` task (adds to the scheduler)
 - uses `.await` to give up the MCU while waiting for the button

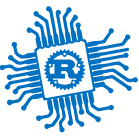
```
1  #[embassy_executor::task(pool_size = 2)]
2  async fn led_blink(mut led: AnyPin) {
3      loop {
4          led.toggle();
5          Timer::after_secs(1).await;
6      }
7  }
8
9  #[embassy_executor::main]
10 async fn main(spawner: Spawner) {
11     // ...
12
13     // init led
14     spawner.spawn(led_blink(led)).unwrap();
15     info!("task started");
16
17     // init button
18     loop {
19         button.wait_for_rising_edge().await;
20         info!("button pressed");
21     }
22 }
```



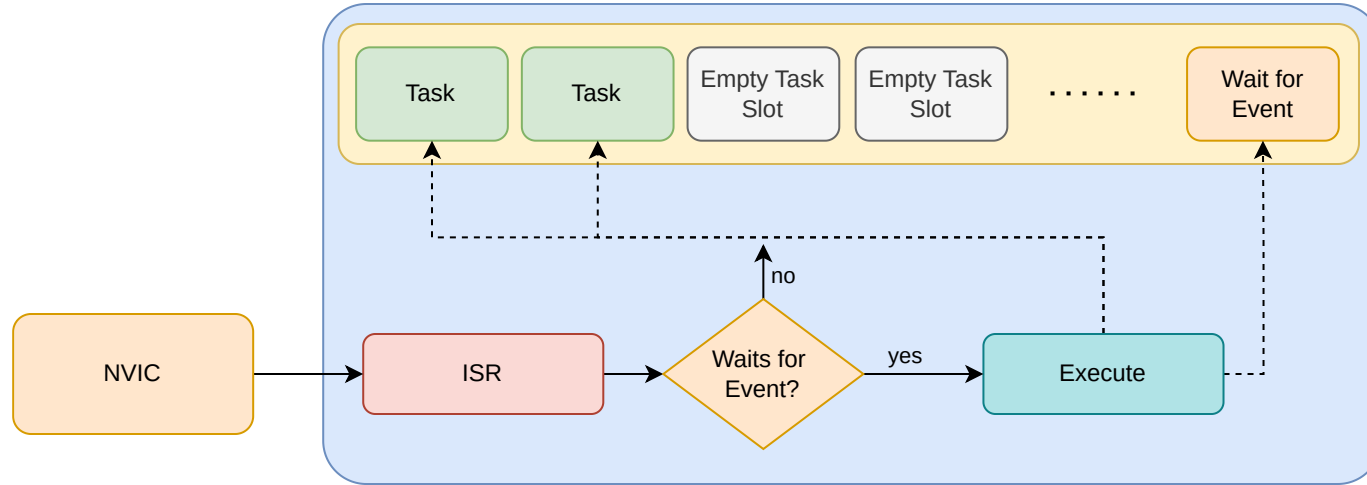
Tasks can stop the executor

- unless awaited, `async` functions are not executed
- tasks have to use `.await` in loops, otherwise they block the scheduler

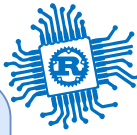
```
1  #[embassy_executor::task]
2  async fn led_blink(mut led: AnyPin) {
3      loop {
4          led.toggle();
5          // this does not execute anything
6          Timer::after_secs(1);
7          // infinite loop without `.await`
8          // that never gives up the MCU
9      }
10 }
11
12 #[embassy_executor::main]
13 async fn main(spawner: Spawner) {
14     // ..
15     loop {
16         button.wait_for_rising_edge().await;
17         info!("button pressed");
18     }
19 }
```



How it works



- sleep when **all tasks wait for events**
- after an ISR is executed
 - if waiting for events, ask every task if it can execute (if the IRQ was what the task was `.await ing` for)
 - if a task is executing, continue the task until it `.await s`
- if a task never `.await s`, the executor does not run and never executes another task



Priority Tasks

- the tasks run in separate *executors*
- triggered from **interrupts**
- will **interrupt any task** running in the **main executor**

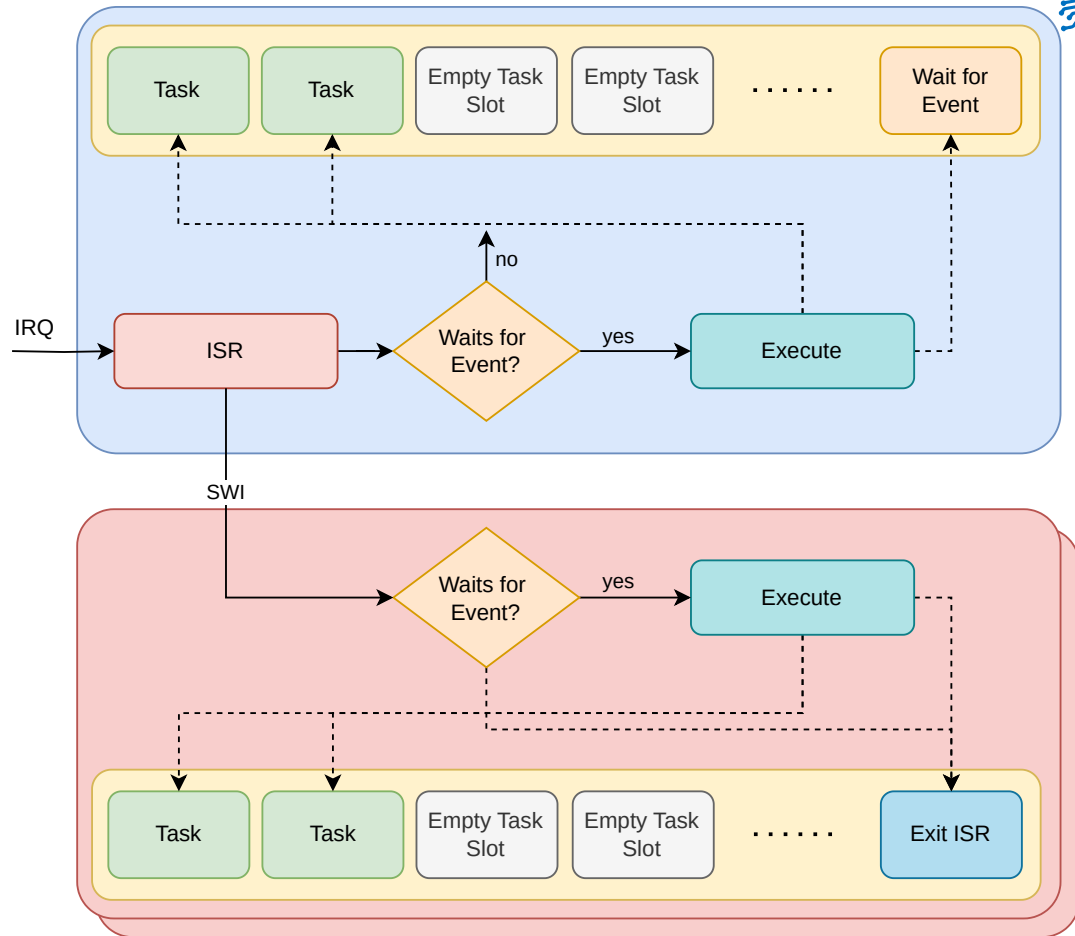
⚠ Tasks that share data between executors require synchronization.

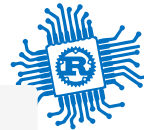
RP2

- use `SWI_IRQ_01` and `SWI_IRQ_01`

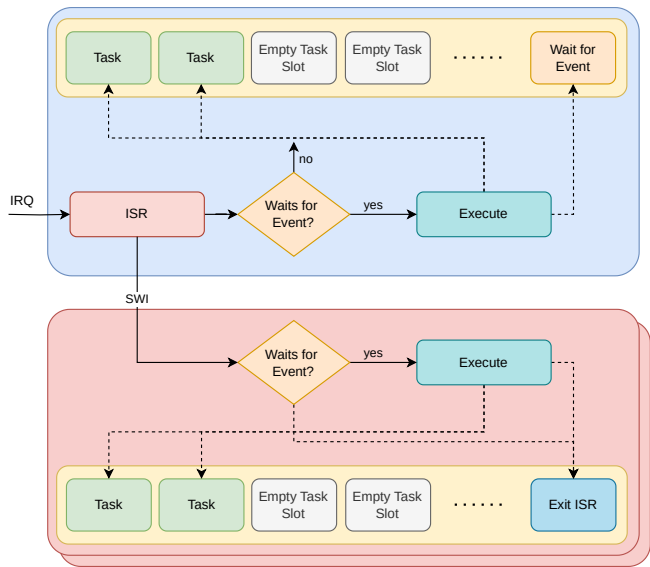
STM32U545RE

- use any interrupt (`UART` , `SPI` ,...)
not used anywhere else





Priority Tasks

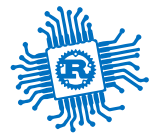


```
#[interrupt]
unsafe fn UART4() {
    EXECUTOR_HIGH.on_interrupt()
}
#[interrupt]
unsafe fn UART5() {
    EXECUTOR_MEDIUM.on_interrupt()
}
```

```
1 // STM32U545RE
2
3 static EXECUTOR_HIGH: InterruptExecutor = InterruptExecutor::new();
4 static EXECUTOR_MEDIUM: InterruptExecutor = InterruptExecutor::new();
5 static EXECUTOR_LOW: StaticCell<Executor> = StaticCell::new();
6
7 #[entry]
8 fn main() -> ! {
9     // High-priority executor: UART4, priority level 2
10    interrupt::SWI_IRQ_1.set_priority(Priority::P2);
11    let spawner = EXECUTOR_HIGH.start(interrupt::UART4);
12    spawner.spawn(run_high()).unwrap();
13
14    // Medium-priority executor: UART5, priority level 3
15    interrupt::SWI_IRQ_0.set_priority(Priority::P3);
16    let spawner = EXECUTOR_MEDIUM.start(interrupt::UART5);
17    spawner.spawn(run_med()).unwrap();
18
19    // Low priority executor: runs in thread mode, using WFE/SEV
20    let executor = EXECUTOR_LOW.init(Executor::new());
21    executor.run(|spawner| {
22        unwrap!(spawner.spawn(run_low()));
23    });
24 }
```

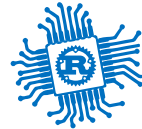


priority executors run in ISRs, lower priority tasks are interrupted



The Future type

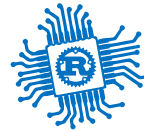
a.k.a Promise in other languages



Bibliography

for this section

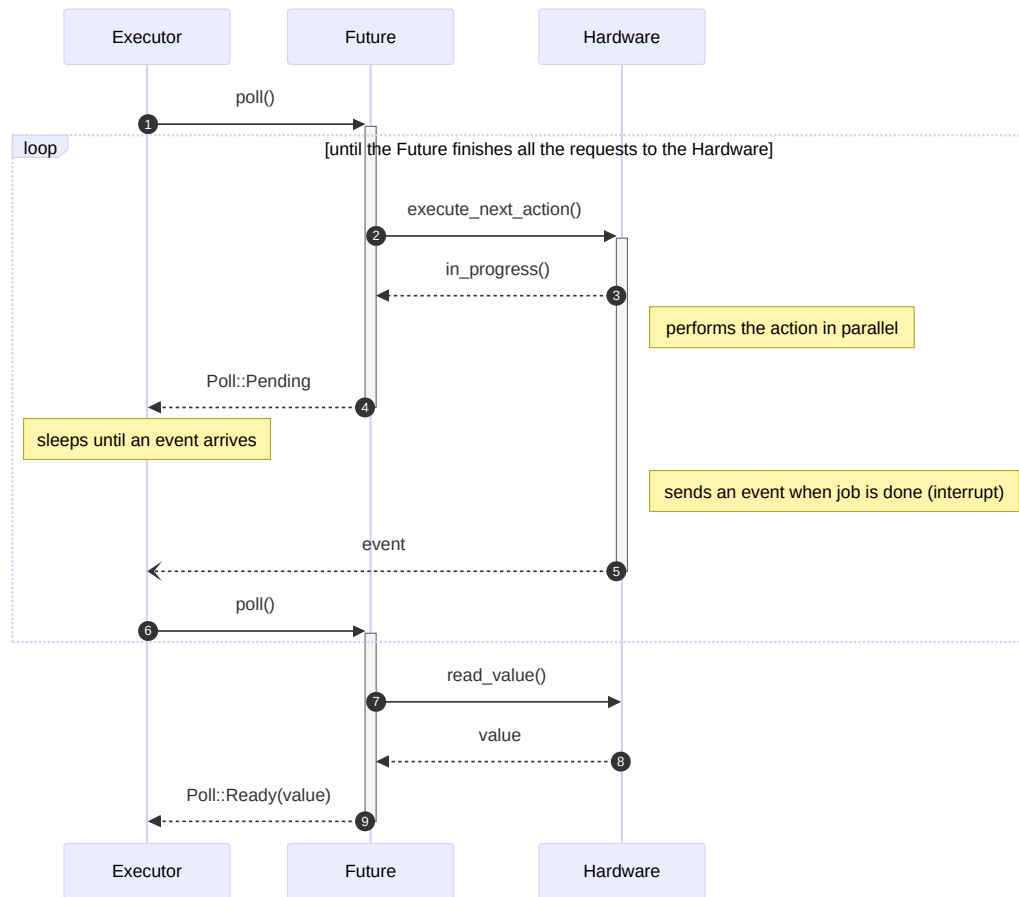
Bert Peters, *How does async Rust work*

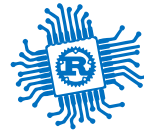


Future

```
enum Poll<T> {  
    Pending,  
    Ready(T),  
}  
  
trait Future {  
    type Output;  
    fn poll(&mut self) -> Poll<Self::Output>;  
}
```

```
fn execute<F>(mut f: F) -> F::Output  
where  
    F: Future  
{  
    loop {  
        match f.poll() {  
            Poll::Pending => wait_for_event(),  
            Poll::Ready(value) => break value  
        }  
    }  
}
```





Implementing a Future

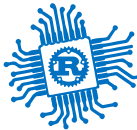
```
enum SleepStatus {
    SetAlarm,
    WaitForAlarm,
}

struct Sleep {
    timeout: usize,
    status: SleepStatus,
}

impl Sleep {
    pub fn new(timeout: usize) -> Sleep {
        Sleep {
            timeout,
            status: SleepStatus::SetAlarm,
        }
    }
}
```

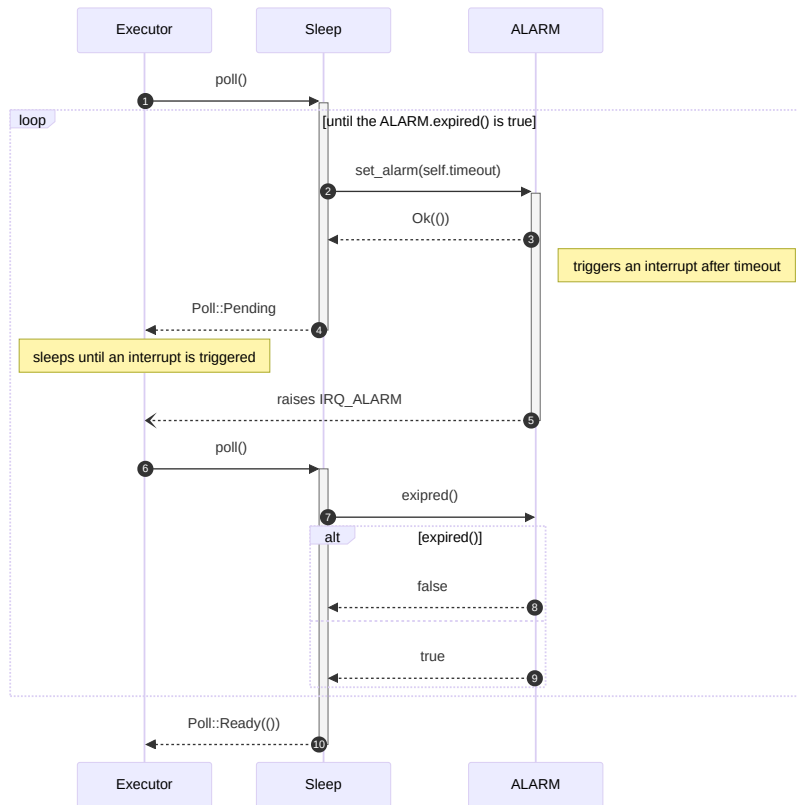
```
impl Future for Sleep {
    type Output = ();

    fn poll(&mut self) -> Poll<Self::Output> {
        loop {
            match self.status {
                SleepStatus::SetAlarm => {
                    ALARM.set_alarm(self.timeout);
                    self.status = SleepStatus::WaitForAlarm;
                }
                SleepStatus::WaitForAlarm => {
                    if ALARM.expired() {
                        return Poll::Ready(());
                    } else {
                        return Poll::Pending
                    }
                }
            }
        }
    }
}
```



Executing Sleep

```
fn poll(&mut self) -> Poll<Self::Output> {  
    loop {  
        match self.status {  
            SleepStatus::SetAlarm => {  
                ALARM.set_alarm(self.timeout);  
                self.status = SleepStatus::WaitForAlarm;  
            }  
            SleepStatus::WaitForAlarm => {  
                if ALARM.expired() {  
                    return Poll::Ready(());  
                } else {  
                    return Poll::Pending;  
                }  
            }  
        }  
    }  
}
```





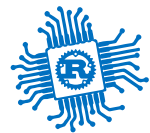
Async Rust

```
async fn blink(mut led: Output<'static, PIN_X>) {  
    led.on();  
    Timer::after_secs(1).await;  
    led.off();  
}
```

Rust rewrites

```
struct Blink {  
    // status  
    status: BlinkStatus,  
    // local variables  
    led: Output<'static, PIN_X>,  
    timer: Option<impl Future>,  
}  
  
impl Blink {  
    pub fn new(led: Output<'static, PIN_X>) -> Blink {  
        Blink { status: BlinkStatus::Part1, led, timer: None }  
    }  
}  
  
fn blink(led: Output<'static, PIN_X>) -> Blink {  
    Blink::new(led)  
}
```

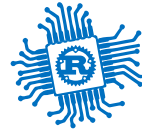
```
impl Future for Blink {  
    type Output = ();  
    fn poll(&mut self) -> Poll<Self::Output> {  
        loop {  
            match self.status {  
                BlinkStatus::Part1 => {  
                    self.led.on();  
                    self.timer1 = Some(Timer::after_secs(1));  
                    self.status = BlinkStatus::Part2;  
                }  
                BlinkStatus::Part2 => {  
                    if self.timer.unwrap().poll() == Poll::Pending {  
                        return Poll::Pending;  
                    } else {  
                        self.status = BlinkStatus::Part3;  
                    }  
                }  
                BlinkStatus::Part3 => {  
                    self.led.off();  
                    return Poll::Ready(());  
                }  
            }  
        }  
    }  
}
```



Async Rust

- the Rust compiler rewrites `async` function into `Future`
- it does not know how to execute them
- executors are implemented into third party libraries

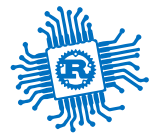
```
1  use engine::execute;
2
3  // Rust rewrites the function to a Future
4  async fn blink(mut led: Output<'static, PIN_X>) {
5      led.on();
6      Timer::after_secs(1).await;
7      led.off();
8  }
9
10 #[entry]
11 fn main() -> ! {
12     blink(); // this returns the Blink future, but does not execute it
13     blink().await; // does not work, as `main` is not an `async` function
14     execute(blink()); // this works, as `execute` executes the Blink future
15 }
```



Executor

```
1  static TASKS: [Option<impl Future>; N] = [None, N];
2
3  fn executor() {
4      loop {
5          // ask all tasks to continue if they have available data
6          for task in TASKS.iter_mut() {
7              if let Some(task) = task {
8                  if Poll::Ready(_) = task.poll() {
9                      *task = None
10                 }
11             }
12         }
13
14         // wait for interrupts
15         cortex_m::asm::wfi();
16     }
17 }
```

- this is a simplified version, `Option<impl Future>` does not work
- the executor is not able to use `TASKS` like this
- an efficient executor will not poll all the tasks, it uses a `waker` that tasks use to signal the executor

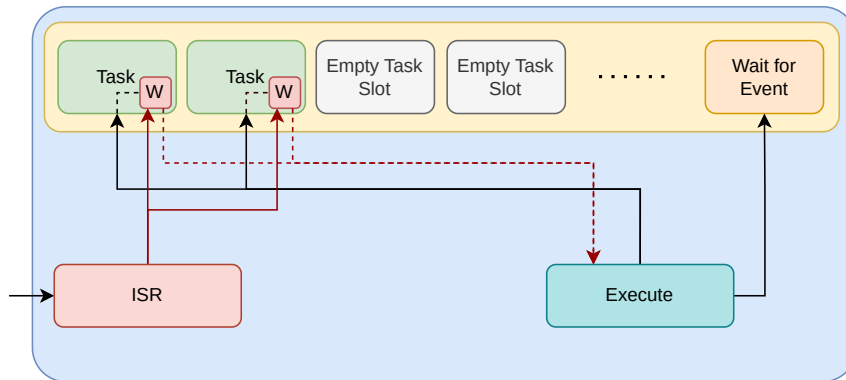


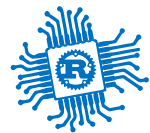
The Future trait

that Rust provides

```
1 trait Future {  
2     type Output;  
3  
4     fn poll(mut self: std::pin::Pin<&mut Self>, cx: &mut Context<'_>) -> Poll<Self::Output>;  
5 }
```

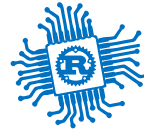
- `Pin` to `mut self`, which means that `self` cannot be moved
- `Context` which provides the `waker`
 - tasks are polled only if they ask the executor (by using the `wake` function)
- `embassy-rs` provides the execution engine





Communication

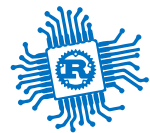
between tasks



Bibliography

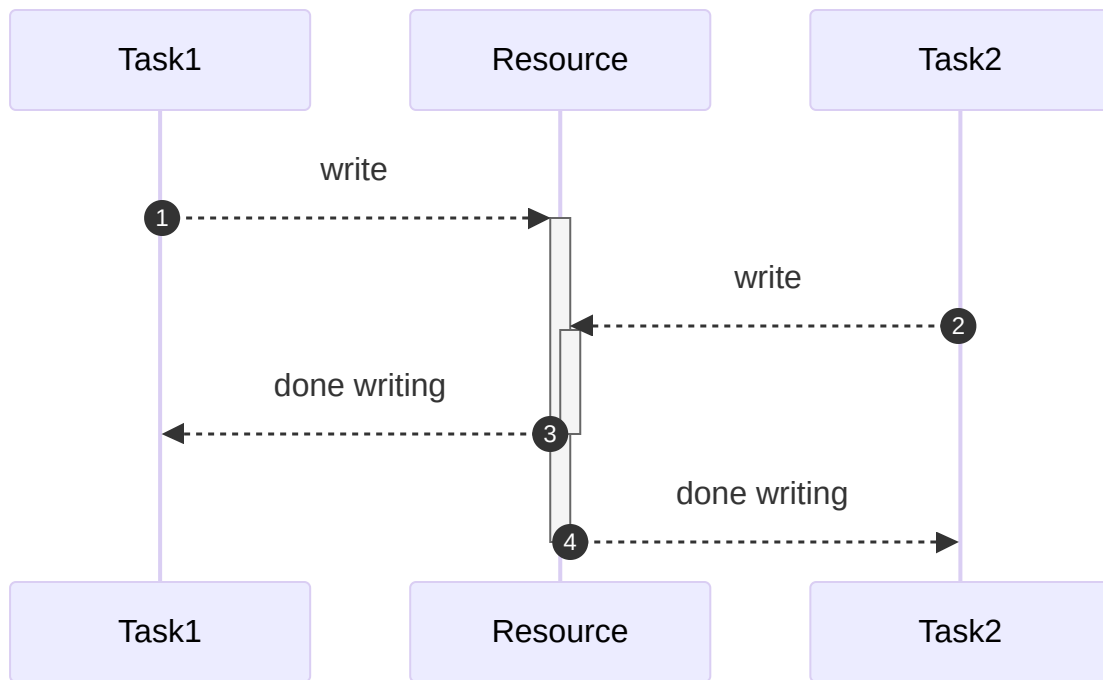
for this section

Omar Hiari, *Sharing Data Among Tasks in Rust Embassy: Synchronization Primitives*



Simultaneous Access

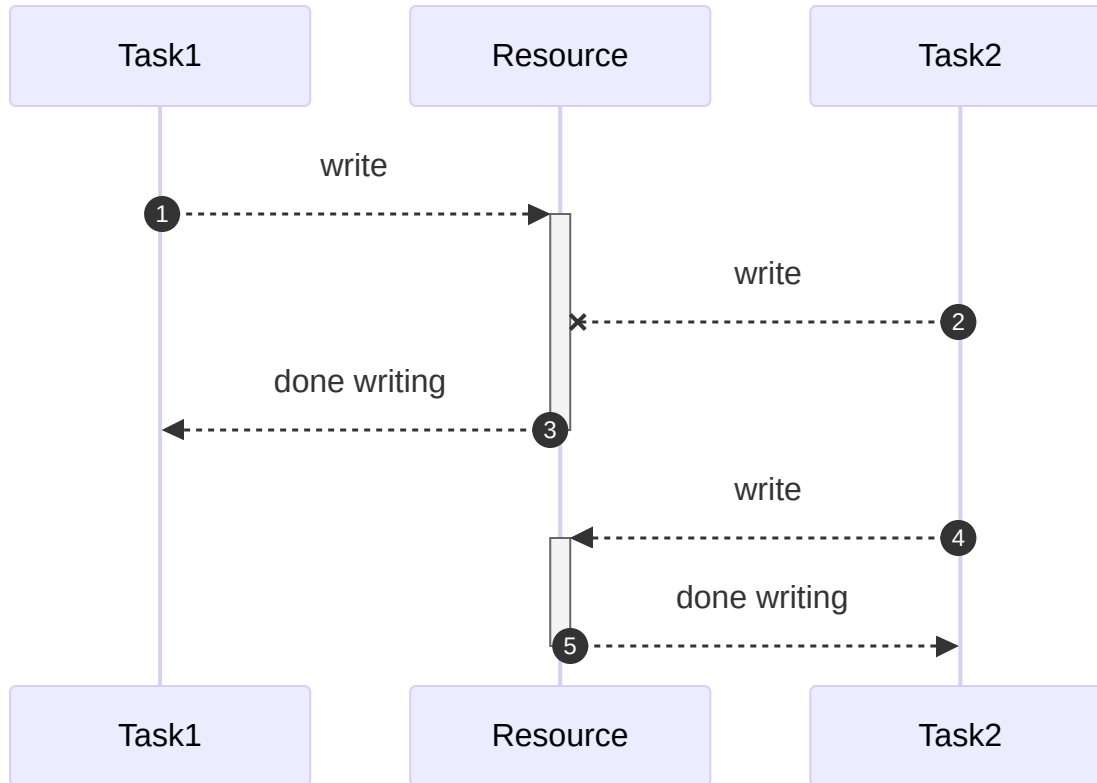
Rust forbids simultaneous writes access

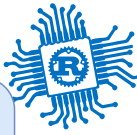




Exclusive Access

we want to sequentially access the resource

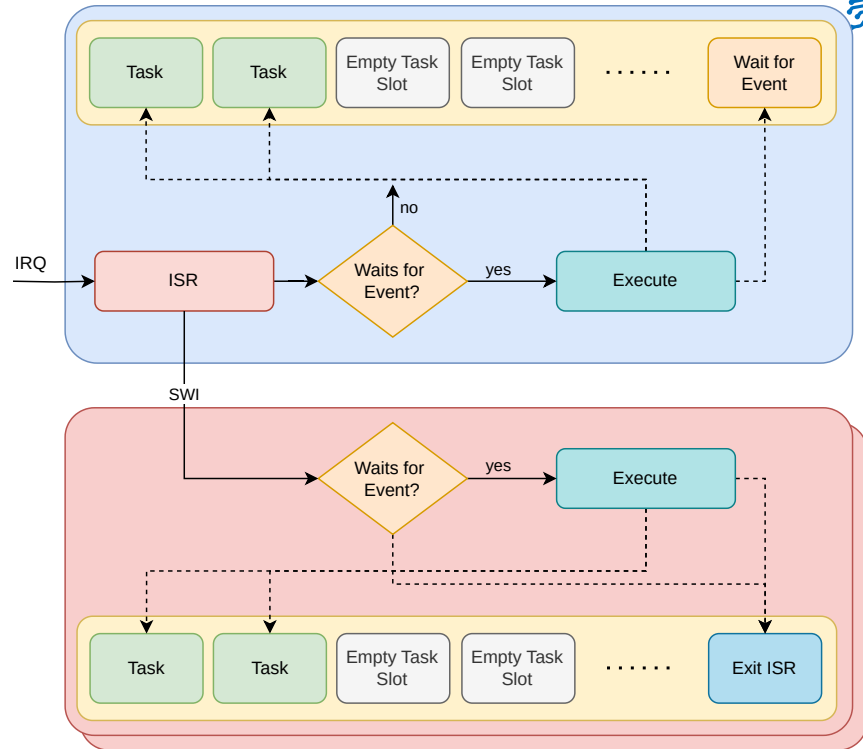




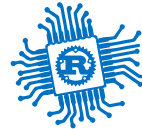
Synchronization

safely share data between tasks

- `NoopMutex` - used for data shared between tasks within the **same executor**
- `CriticalSectionMutex` - used for data shared between multiple executors, ISRs and cores
- `ThreadModeMutex` - used for data shared between tasks within **low priority executors** (**not** running in **ISRs** mode) running on a **single core**



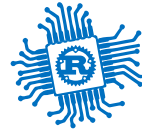
- ISRs are executed in parallel with tasks
- embassy allows registering priority executors, that run tasks in ISRs
- some MCUs have multiple cores



Blocking Mutex

no `.await` allowed while the mutex is held

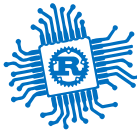
```
1 use embassy_sync::blocking_mutex::Mutex;
2
3 struct Data { /* ... */ }
4
5 static SHARED_DATA: Mutex<ThreadModeRawMutex, RefCell<Data>> = Mutex::new(RefCell::new(Data::new(/* ... */)));
6
7 #[embassy_executor::task]
8 async fn task1() {
9     // Load value from global context, modify and store
10     SHARED_DATA.lock(|f| {
11         let data = f.borrow_mut();
12         // edit data
13         f.replace(data);
14     });
15 }
```



Async Mutex

`.await` is allowed while the Mutex is held, it will release the Mutex while `await` ing

```
1  use embassy_sync::mutex::Mutex;
2
3  struct Data { /* ... */ }
4
5  static SHARED: Mutex<ThreadModeRawMutex, Data> = Mutex::new(Data::new(/* ... */));
6
7  #[embassy_executor::task]
8  async fn task1() {
9      // Load value from global context, modify and store
10     {
11         let mut data = SHARED_DATA.lock().await;
12         // edit *data
13         Timer::after(Duration::from_millis(1000)).await;
14     }
15 }
```



Channels

send data from a task to another

Embassy provides four types of channels synchronized using `Mutex` s

Type	Description
<code>Channel</code>	A Multiple Producer Multiple Consumer (MPMC) channel. Each message is only received by a single consumer.
<code>PriorityChannel</code>	A Multiple Producer Multiple Consumer (MPMC) channel. Each message is only received by a single consumer. Higher priority items are shifted to the front of the channel.
<code>Signal</code>	Signalling latest value to a single consumer.
<code>PubSubChannel</code>	A broadcast channel (publish-subscribe) channel. Each message is received by all consumers.

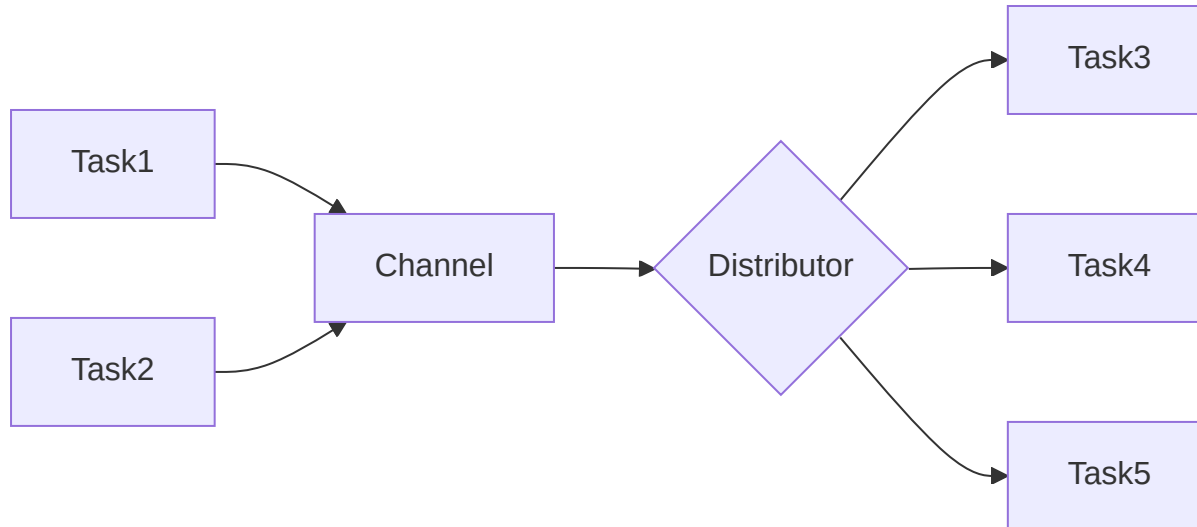


Channel and Signal

sends data from one task to another

Channel - A Multiple Producer Multiple Consumer (MPMC) channel. Each message is only received by a single consumer.

Signal - Signalling latest value to a single consumer.

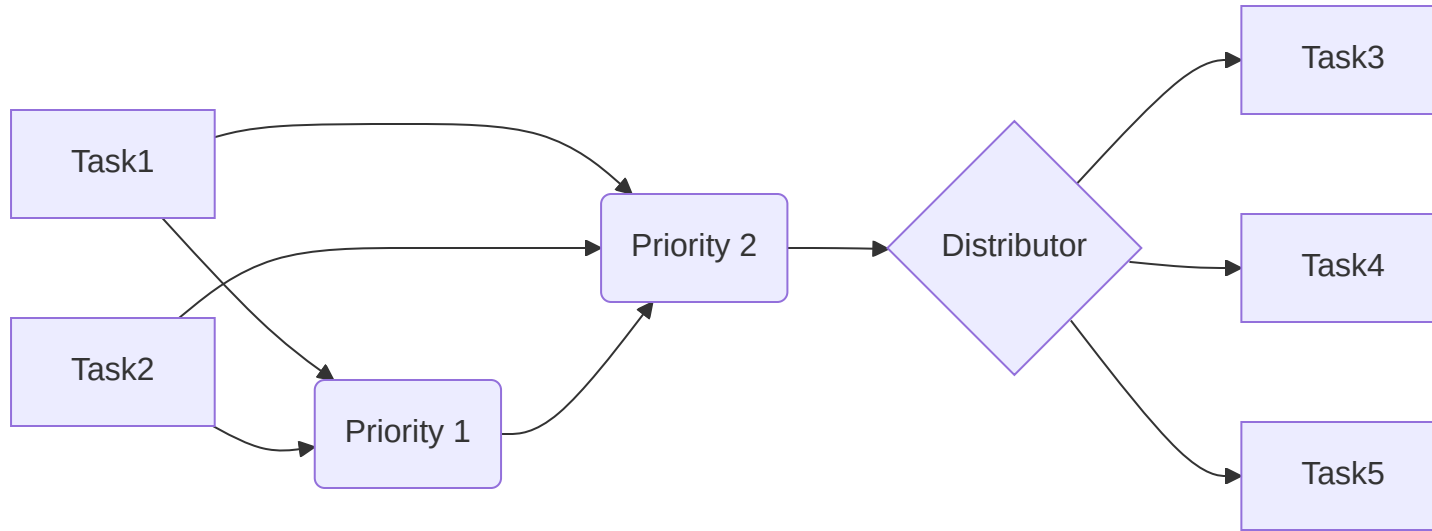


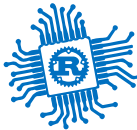


PriorityChannel

sends data from one task to another with a priority

`PriorityChannel` - A Multiple Producer Multiple Consumer (MPMC) channel. Each message is only received by a single consumer. Higher priority items are shifted to the front of the channel.

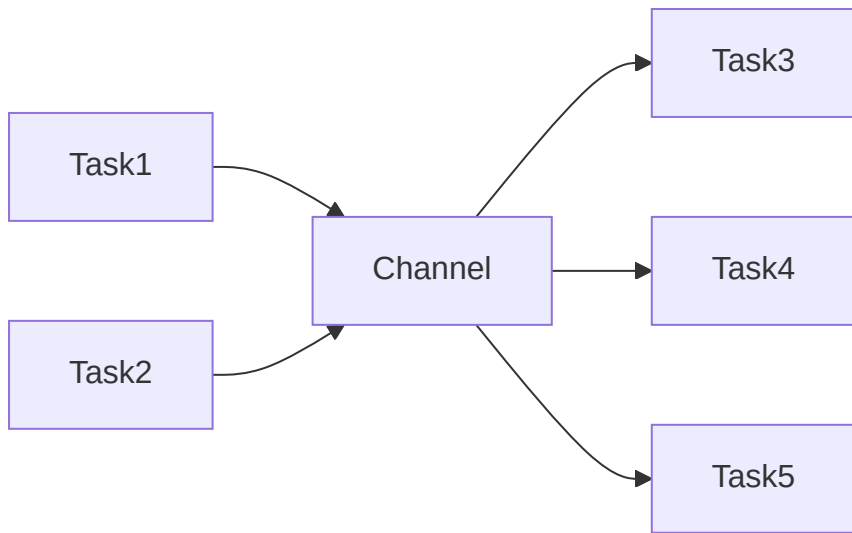


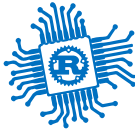


PubSubChannel

sends data from one task to all receiver tasks

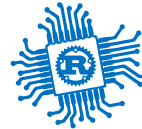
`PubSubChannel` - A broadcast channel (publish-subscribe) channel. Each message is received by all consumers.





Channel Example

```
1  enum LedState { On, Off }
2  static CHANNEL: Channel<ThreadModeRawMutex, LedState, 64> = Channel::new();
3
4  #[embassy_executor::main]
5  async fn main(spawner: Spawner) {
6      // init led
7      spawner.spawn(execute_led(CHANNEL.sender(), Duration::from_millis(500))));
8      loop {
9          match CHANNEL.receive().await {
10             LedState::On => led.on(),
11             LedState::Off => led.off()
12          }
13      }
14  }
15
16  #[embassy_executor::task]
17  async fn execute_led(control: Sender<'static, ThreadModeRawMutex, LedState, 64>, delay: Duration) {
18      let mut ticker = Ticker::every(delay);
19      loop {
20          control.send(LedState::On).await;
21          ticker.next().await;
22          control.send(LedState::Off).await;
23          ticker.next().await;
```



Conclusion

we talked about

- Preemptive & Cooperative Concurrency
- Asynchronous Executor
- `Future` s and how Rust rewrites `async` function
- Communication between tasks