# Tock Embedded OS Training

SOSP 2017

*Please make sure you have completed all of the tutorial pre-requisites. If you prefer, you can download a virtual machine image with all the pre-requisites already installed.*

`https://github.com/helena-project/tock/tree/master/doc/courses/sosp/README.md` aka `https://goo.gl/s17fy8`

# Tock is a...

1. Secure
2. Embedded
3. Operating System
4. for Low Resource
5. Microcontrollers

# Secure

# ~~*Secure*~~ Safe

Tock has isolation primitives that allow you to build secure systems.

# Embedded

## Definition A

*Kernel, applications, and hardware are tightly integrated.*

## Definition B

*You'll likely be writing the kernel.*

# Operating System

Tock itself provides services to components in the system:

- Scheduling
- Communication
- Hardware multiplexing

# Low Resource

- 10's of μA average power draw
- 10's of kBs of RAM
- Moderate clock speeds

# Microcontrollers

System-on-a-chip with integrated flash, SRAM, CPU and a bunch of hardware controllers.

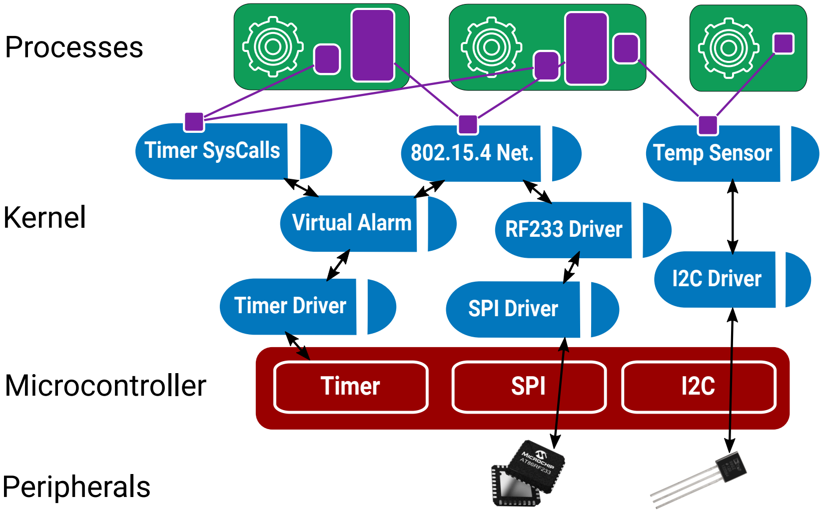
Typically:

- Communication: UART, SPI, I2C, USB, CAN...
- External I/O: GPIO, external interrupt, ADC, DAC
- Timers: RTC, countdown timers

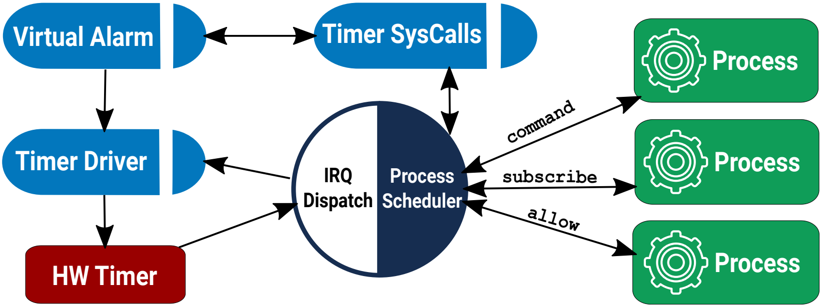
Maybe...

- Radio (Bluetooth, 15.4)
- Cryptographic accelerators
- Other specialized hardware...

# Two types of components: capsules and processes



# Two types of scheduling: cooperative and preemptive

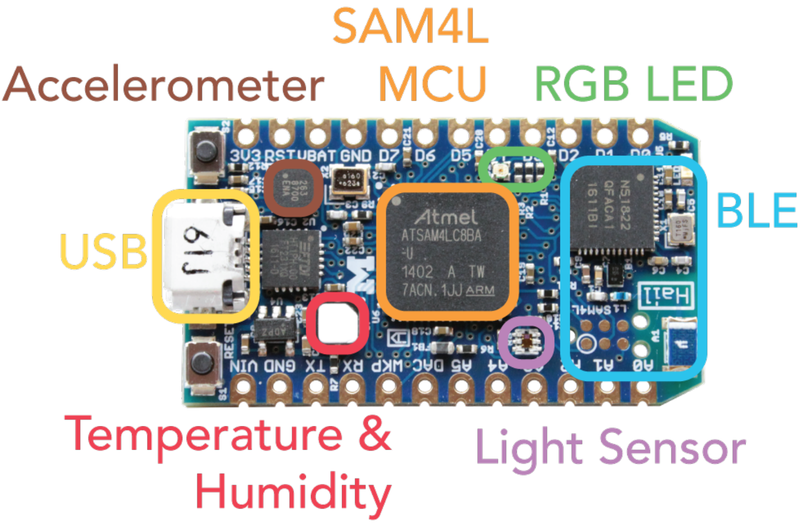


# Agenda Today

1. Intro to hardware, tools and development environment
2. Add functionality to the Tock kernel
3. Write an end-to-end Bluetooth Low Energy environment sensing application.

# Part 1: Hardware, tools and development environment

# Hail


SAM4L
MCU
Accelerometer
RGB LED
USB
BLE
Temperature &
Humidity
Light Sensor

# Binaries on-board

Bootloader

Kernel

Processes

# Tools

- `make` (just instrumenting `xargo`)
- Rust (nightly for `asm!`, compiling `core`, etc)
- `xargo` to automate compiling base libraries
- `arm-none-eabi` GCC/LD to link binaries
- `tockloader` to interact with Hail and the bootloader

# Tools: `tockloader`

Write a binary to a particular address in flash

```
$ tockloader flash --address 0x1000 \
    target/thumbv7em-none-eabi/release/hail.bin
```

Program a process in Tock Binary Format[1]:

```
$ tockloader install myapp.tab
```

Restart the board and connect to the debug console:

```
$ tockloader listen
```

[1]TBFs are relocatable process binaries prefixed with headers like the package name. `.tab` is a tarball of TBFs for different architectures as well as a metadata file for `tockloader`.

# Check your understanding

1. What kinds of binaries exist on a Tock board? Hint: There are three, and only two can be programmed using `tockloader`.
2. Can you point to the chip on the Hail that runs the Tock kernel? How about the processes?
3. What steps would you follow to program a processes onto Hail? What about to replace the kernel?

# Hands-on: Set-up development environment

1. Compile and flash the kernel
2. Compile and program `ble-env-sense` service
3. (Optional) Add some other apps from the repo, like `blink` and `sensors`
4. (Optional) Familiarize yourself with `tockloader` commands
   - `uninstall`
   - `list`
   - `erase-apps`

# Part 2: User space

# System calls

| Call | Target | Description |
|---|---|---|
| command | Capsule | Invoke an operation on a capsule |
| allow | Capsule | Share memory with a capsule |
| subscribe | Capsule | Register an upcall |
| memop | Core | Modify memory break |
| yield | Core | Bloc until next upcall is ready |

# Rust System calls: `command` & `allow`

```
pub unsafe fn command(major: u32, minor: u32,
  arg: isize) -> isize;

pub unsafe fn allow(major: u32, minor: u32,
                    slice: &[u8]) -> isize;
```

# Rust System calls: `subscribe`

```rust
type ExternFn =
  extern fn (usize, usize, usize, *const usize);

pub unsafe fn subscribe(major: u32, minor: u32,
  cb: ExternFn, ud: *const usize) -> isize {
```

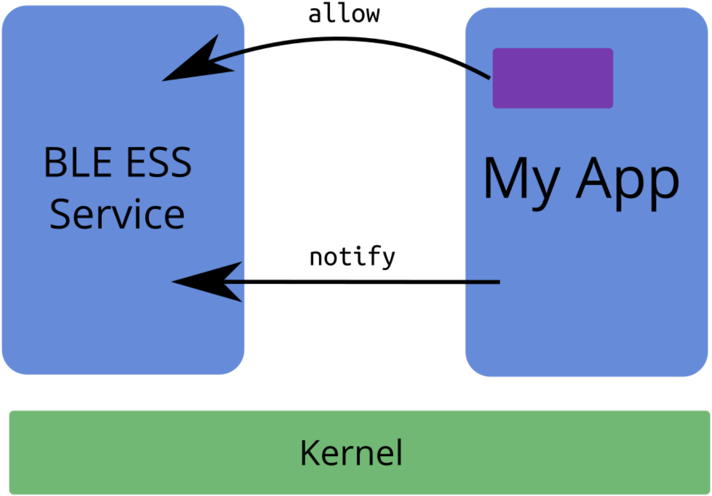
# Rust System calls: yieldk & yieldk_for

```
pub fn yieldk();

pub fn yieldk_for<F: Fn() -> bool>(cond: F) {
    while !cond() { yieldk(); }
}
```

# Example: printing to the debug console

```
pub fn write(string: Box<[u8]>) {
    let done: Cell<bool> = Cell::new(false);
    syscalls::allow(DRIVER_NUM, 1, string);
    syscalls::subscribe(DRIVER_NUM, 1, callback,
          &done as *const _ as usiz);
    syscalls::command(DRIVER_NUM, 1, string.len());
    yieldk_for(|| done.get())
}

extern fn callback(_: usize, _: usize, _: usize,
                   ud: *const usize) {
    let done: &Cell<bool> = unsafe {
        mem::transmute(ud)
    };
    done.set(true);
}
```

# Inter Process Communication (IPC)



# Current Rust userland

## Supported drivers

- Debug console
- Timer
- Sensors:
  - Accelerometer & magnetometer
  - Ambient light
  - Temperature
- IPC

## Caveats

- No global variables allowed!
- Fixed code offset
- Blocking library calls only

# Check your understanding

1. How does a process perform a blocking operation? Can you draw the flow of operations when a process calls `delay_ms(1000)`?
2. What is a Grant? How do processes interact with grants? Hint: Think about memory exhaustion.

# Hands-on: Write a BLE environment sensing application

1. Get a Rust application running on Hail
2. Periodically sample on-board sensors
3. Extend your app to report through the `ble-env-sense` service

# Part 3: The kernel

# Trusted Computing Base (`unsafe` allowed)

- Hardware Abstraction Layer
- Board configuration
- Event & Process scheduler
- Rust `core` library
- Core Tock primitives

```
kernel/
chips/
```

# Capsules (`unsafe` not allowed)

- Virtualization
- Peripheral drivers
- Communication protocols (IP, USB, etc)
- Application logic

`capsules/`

# Constraints

### Small isolation units

Breaking a monolithic component into smaller ones should have low/no cost

### Avoid memory exhaustion in the kernel

No heap. Everything is allocated statically.

### Low communication overhead

Communicating between components as cheap as an internal function call. Ideally inlined.

# Event-driven execution model

```rust
pub fn main<P, C>(platform: &P, chip: &mut C,
                  processes: &mut [Process]) {
    loop {
        chip.service_pending_interrupts();
        for (i, p) in processes.iter_mut().enumerate() {
            sched::do_process(platform, chip, process);
        }

        if !chip.has_pending_interrupts() {
            chip.prepare_for_sleep();
            support::wfi();
        }
    }
}
```

# Event-driven execution model

```
fn service_pending_interrupts(&mut self) {
    while let Some(interrupt) = get_interrupt() {
        match interrupt {
            ASTALARM => ast::AST.handle_interrupt(),
            USART0 => usart::USART0.handle_interrupt(),
            USART1 => usart::USART1.handle_interrupt(),
            USART2 => usart::USART2.handle_interrupt(),
            ...
        }
    }
}
```

# Event-driven execution model

```
impl Ast {
    pub fn handle_interrupt(&self) {
        self.clear_alarm();
        self.callback.get().map(|cb| { cb.fired(); });
    }
}
impl time::Client for MuxAlarm {
    fn fired(&self) {
        for cur in self.virtual_alarms.iter() {
            if cur.should_fire() {
                cur.armed.set(false);
                self.enabled.set(self.enabled.get() - 1);
                cur.fired();
            }
        }
    }
}
```

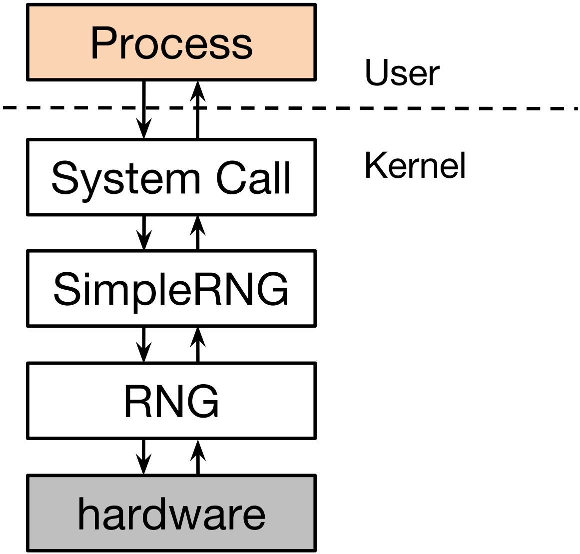



Figure: Capsules reference each other directly, assisting inlining

# The mutable aliases problem

```
enum NumOrPointer {
  Num(u32),
  Pointer(&mut u32)
}

// n.b. will not compile
let external : &mut NumOrPointer;
match external {
  Pointer(internal) => {
    // This would violate safety and
    // write to memory at 0xdeadbeef
    *external = Num(0xdeadbeef);
    *internal = 12345;  // Kaboom
  },
  ...
}
```

# Interior mutability to the rescue

| Type | Copy-only | Mutual exclusion | Opt. | Mem Opt. |
|---|---|---|---|---|
| `Cell` | ✓ | ✗ | ✓ | ✓ |
| `VolatileCell` | ✓ | ✗ | ✗ | ✓ |
| `TakeCell` | ✗ | ✓ | ✗ | ✓ |
| `MapCell` | ✗ | ✓ | ✓ | ✗ |

```
pub struct Fxos8700cq<`a> {
  i2c: &`a I2CDevice,
  state: Cell<State>,
  buffer: TakeCell<`static, [u8]>,
  callback:
    Cell<Option<&`a hil::ninedof::NineDofClient>>,
}

impl<`a> I2CClient for Fxos8700cq<`a> {
  fn cmd_complete(&self, buf: &`static mut [u8]) { ... }
}

impl<`a> hil::ninedof::NineDof for Fxos8700cq<`a> {
  fn read_accelerometer(&self) -> ReturnCode { ... }
}

pub trait NineDofClient {
  fn callback(&self, x: usize, y: usize, z: usize);
}
```

# Check your understanding

1. What is a `VolatileCell`? Can you find some uses of `VolatileCell`, and do you understand why they are needed? Hint: look inside `chips/sam4l/src`.
2. What is a `TakeCell`? When is a `TakeCell` preferable to a standard `Cell`?

# Hands-on: Write and add a capsule to the kernel

1. Read the Hail boot sequence in `boards/hail/src/main.rs`
2. Write a new capsule that prints "Hello World" to the debug console.
3. Extend your capsule to print "Hello World" every second
4. Extend your capsule to read and report the accelerometer
5. Extra Credit: Write a 9dof virtualization capsule.