OWNERSHIP IS THEFT: EXPERIENCES BUILDING AN EMBEDDED OS IN RUST

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October 4th, 2015

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- Lots of changes in embedded applications hardware since
- TinyOS written in nesC (a dialect of C)
- Decided to revisit the design of an embedded OS and write it in a safe language.

"When we ported TinyOS from C to nesC it only took a few weeks!"

But here we are a year later...

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We didn't take into account how much our choice of language would affect our system's design.

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But we can't forgot that system design and language design are actually ***co-dependent***!

- Background
    - Microcontrollers
    - Tock: an new embedded OS
    - Rust
- Two Challenges
- Conclusion

BACKGROUND - MICROCONTROLLERS

Who uses Microncontrollers?

Not Your Grandchildren's Processor

- Very little memory
  - Range 16-512KB RAM
- Crashes are particularly expensive:
  - Cannot assume user intervation (no screen or keyboard)
  - High stakes: implanted medical devices, home automation...
- Limited hardwared protection:
  - Specifically, no virtual memory

Limited Hardware Motivates Language Choice

- Too little memory to use processes for isolation
- Crashes are expensive, so we should catch as many bugs as possible at compile-time.

BACKGROUND – TOCK

Tock is an embedded operating system we’ve been building for about a year.

Why a *New* OS?

- Existing systems: TinyOS, Contiki, FreeRTOS
- New requirements
- New hardware
- New programming language(s)

New Requirements

- Traditional embedded operating systems were design for single app devices.
  - Software updated never or rarely.
  - Everything is trusted, including the app.
- New applications are *platforms*.
  - Software updates
  - Third-party apps
- Kernel extensions should really be isolated
  - Drivers may come from a variety of sources.
  - …like Linux drivers but for your defibrillator!

Microcontrollers have improved drastically

- From 16-bit arch @ 6Mhz to 32-bit arch @ 48Mhz
- More busses, more timers, AES encryption, etc in hardware
- A system-call interfance no longer a performance barrier

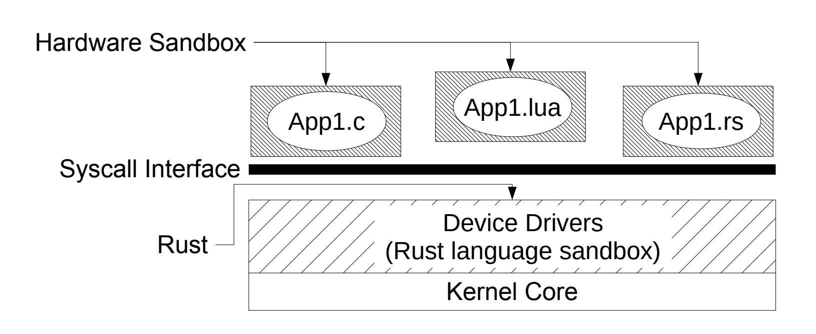
Some limited support for hardware protection

- Memory Protection Unit in ARM Cortex-M series

Rust, a new *safe* language without the runtime overhead

- Memory and type safety
- Eliminate large classes of bugs at *compile time*
- Strong type-system can allow component isolation
- Low-level primitives can enable rich security systems

Tock Architecture



BACKGROUND - RUST

Why Rust?

Two distinguishing properties from other safe languages:

- Enforces memory and type safety without a garbage collector
- Explicit separation of trusted vs. untrusted code
  - Untrusted code is strictly bound by the type system
  - Trusted code can circumvent the type system

Rust avoids the runtime overhead of garbage collection by using *ownership* to determine when to free memory at *compile-time*.

Ownership for Safety

Each Value has a Single Owner

Key Property

When the owner goes out of scope, we can deallocate memory for the value.

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Memory for the value `43` is allocated and bound to the variable `x`.

```
{
  let x = 43
}
```

When the scope exits, `x` is no longer valid and the memory is "freed"

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Single owner means *no aliasing*, so values are either copied or moved between variables.

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This is an error:

```
{
  let x = Foo::new();
  let y = x;
  println("{}", x);
}
```

because `Foo::new()` has been moved from `x` to `y`, so `x` is no longer valid.

Functions must explicitly hand ownership back to the caller:

```
fn bar(x: Foo) -> Foo {
  // Do stuff
  x // <- return x
}
```

Or can use **borrows**: a type of reference which does not invalidate the owner.

```
fn bar(x: &mut Foo) {
  // Do stuff
  // the borrow is implicitly released.
}

fn main() {
  let mut x = Foo::new();
  bar(&mut x);
  println!("{}", x); // x still valid
}
```

Borrows

Borrows are resolved at compile-time, with some constraints:

- A value can only be *mutably* borrowed if there are no other borrows of the value.
- Borrows cannot outlive the value they borrow.
- Values cannot be moved while they are borrowed.

CHALLENGES

1. Ownership vs. Cycles
2. Closures as Callbacks
3. Memory allocation for long-lived closures (see paper)

CHALLENGES - OWNERSHIP VS. CYCLES

Ownership vs. Cycles

Circular references between OS modules are ubiquitous.

`RadioDriver` has to notify `IPStack` of incoming packets, while `IPStack` uses the `RadioDriver` to send packets.

```
impl IPStack {
  fn send(&mut self, packet) {
    packet.concat_ip_header_to_pkt();
    self.radio.send(packet);
  }
}
impl RadioDriver {
  fn on_receive(&mut self, packet) {
    self.ip_stack.incoming(packet);
  }
}
```

Several Possible Solutions

1. Combine mutually dependent modules
2. Message passing instead of shared state
3. Use unsafe language features
4. Use explicitly aliasable reference types

Combine Mutually Dependent Modules

```
impl IPStackAndAlsoRadioDriver {
  fn send(&mut self, packet) {
    packet.concat_ip_header_to_pkt();
    // write packet to radio
  }

  fn on_receive(&mut self, packet) {
    // just handle here
  }
}
```

- No modularity/extensibility.
- Least upper bound of trust

Message Passing

```
impl IPStack
  fn send(&mut self, packet) {
    packet.concat_ip_header_to_pkt();
    self.packet_out_chan.send(packet);
  }

  fn do_work() {
    self.process_pkt(self.packet_in_chan.recv());
  }
}
```

Might work if you're willing to have threads and dynamically allocate or block.

Use `unsafe` Features

```
pub static mut IPSTACK : IPStack = ...;

impl UDP {
  fn send(&self, packet) {
    unsafe { // Unsafe to borrow a mutable static
        IPSTACK.send(packet);
    }
  }
}
```

Requires including trusting virtually every component in the system.

Explicitly Sharable Reference Types

- A small bit of `unsafe` to make a reference type that is aliasable.
    - E.g. `core::cell::RefCell` dynamically checks borrow rules
- Loose compile-time guanratees

Explicitly Sharable Reference Types

This is what we are using.

- Had to completely eliminate concurrency in the kernel
- Be very cautious about who gets shared references.
- Enqueue all interrupts to run in main kernel thread
  - Avoid any work in interrupt handlers
  - Lose hardware interrupt priorities
  - Probably OK for performance, although still need to validate

CHALLENGES - CLOSURES AS CALLBACKS

Problem

Asyncornous code in C usually uses one of two mechanism:

- State-machines
- Function pointers + stack ripping

Both are:

- Difficult to read/write/maintain
- Bug prone

Closures to the Rescue?

Event-driven application languages (e.g. JavaScript) address this problem by specifying callbacks as closures at the callsite.

```
var count = 0;

setInterval(function() {
  console.log(count + " clicks");
}, 2000);

onClick(function() {
  count += 1;
});
```

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});
```

Rust has closures… so we can just do that!

Ownership Strikes Again

In Rust, closures have two options:

- Take ownership of closed over variables
- Complete before returning to the caller

```
let mut x = 0;

setInterval(move ||
  println!("{} clicks", x);
}, 2000);

// x is no longer valid in this context, and we
// cannot create the closure for onClick
```

Result: Oversharing vs. Undersharing

We have to carefully partition state between caller and callbacks. But that's very hard to get right.

Overshare with the callback:

```
// No other code can access any LEDs
setTimeout(|| {
  leds.activityToggle();
}, 2000);
```

Partition resources into tiny interfaces that are hard to manage:

```
setTimeout(|| {
  activityLed.toggle();
}, 2000);
```

CONCLUSION

Conclusion

- Embedded systems have unique requirements
- Rust seems well-suited for a resource constrained OS
    - Type- and memory- safe with no garbage collector
- Tock: an embedded OS
    - Comines hardware and language protection
- Ownership is both the hero and the villan in our story
- Closures not as powerful as we're familiar from other languages

In the paper

- Proposal to expose threads in the type system

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System design and language design are *not* independent.

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Open Questions

How should we design operating systems to best leverage safe languages?

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How can we design safe languages to better target low-level systems?

Thanks!

`http://tockos.org`
`http://github.com/helena-project/tock`