# Design and Implementation of an Embedded Python Run-Time System

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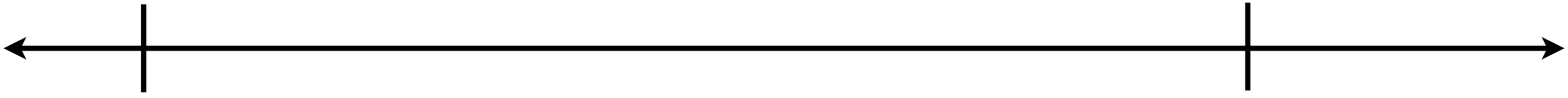
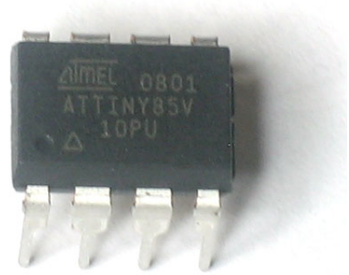
# The computing landscape

# Microcontrollers: They're *everywhere*.

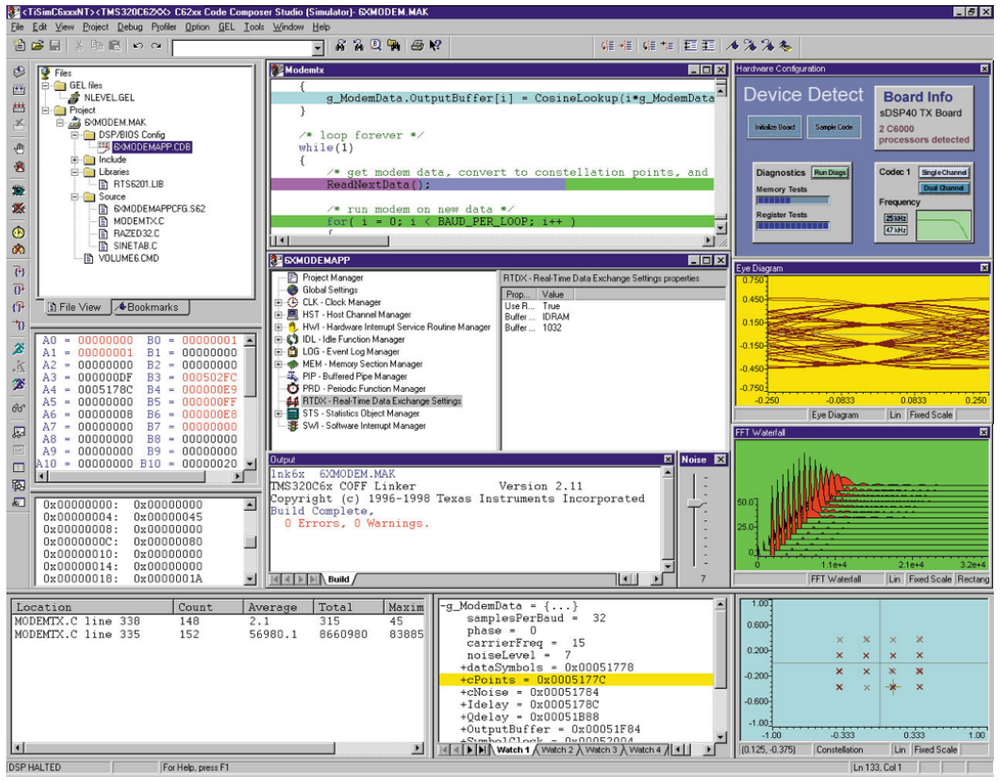




Uncountable? ~10bil ~1bil ~1000s

# Microcontrollers: They're *everywhere*.

- **Virtually no run-time support** *(yet)*
  - Storage?
  - Memory allocation?
  - Interrupt handlers?
  - Console?



# Microcontrollers: They're *everywhere*.

- **32-bit ARM Cortex-M3**
  - 64-128KB RAM
  - Up to 512KB Flash
  - 50-100MHz
- **Interpreters on microcontrollers?**
  - Java Card
  - eLua
  - Python-on-a-chip

# Owl: A Development Environment for Microcontrollers

- **Run-time and toolchain**
  - Open-source
    - Based on p14p
  - Interactive prompt
  - Profilers
  - Programmers
  - A lot more
- **It works. Today.**
- **Focus on two parts today**
  - Store Python objects
  - Call C functions

```
rixner@delaware ~ $ mcu ipm
Owl Interactive Prompt
Using Python 2.7.3
Running firmware 84bcd563345b+. (06Jun12, 01:46PM, tbarr)
Status: ([], [], [], [], [], [], [])

python> a = 3
python> print a + 1
4
python> import lights
python> lights.one.on()
python> def f(x):
        return x * x

python> f(3)
9
python>
```

# Representing programs

- **Python source code**

```
def foo():
    a = 'foo'
b = (42, 'bar')
c = 27 + 3
```

# Representing programs

- **Compiler builds code objects**
  - Bytecode to represent user program

```
def foo():
    a = 'foo'
    b = (42, 'bar')
    c = 27 + 3
```

Bytecodes:

```
LOAD_CONST 0
STORE_NAME 0
...
```

# Representing programs

- **Must include data along with code**
  - Constants, names, etc.
  - .pyc file, .class file

Bytecodes:

```
LOAD_CONST 0
STORE_NAME 0
...
```

Constants:

```
0: 'foo'
1: (42, 'bar')
...
```

# Loading programs

File:

```
0: 'foo'
1: (42, 'bar')
...
```

Memory

# Loading programs

File:

```
0: 'foo'
1: (42, 'bar')
...
```

Memory

```
str:
```

# Loading programs

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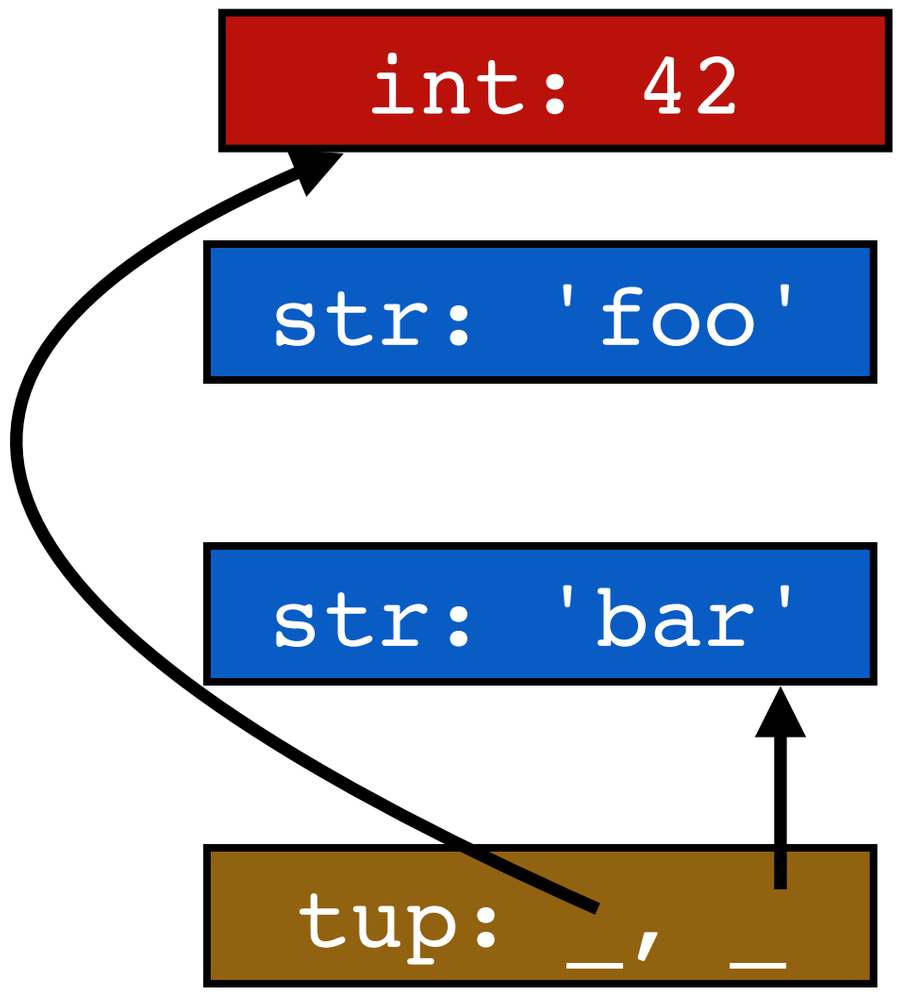
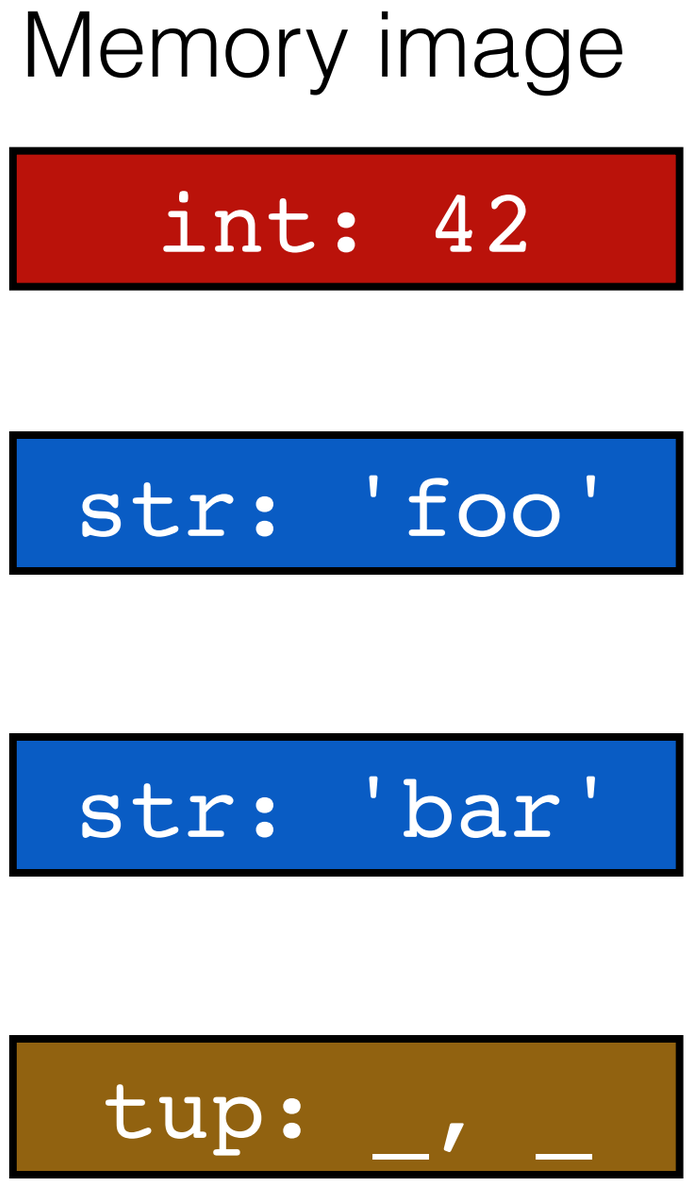


# Loading programs

- **Intermediate files**
  - Python .pyc file, Java .class file, etc.
  - Loaded at runtime, then executed
- **Load before execution**
  - Copy and transform
    - Link compound objects with references
- Makes sense on x86
  - RAM is plentiful
- Doesn’t on microcontroller
  - Can't afford to copy anything

# Loading programs

- **Owl memory image**
  - Unique on interpreted embedded systems
  - Store objects in form that is used by the VM
    - Object headers
    - Byte-order
- How do we store compound objects?



# Loading programs


- **Packed tuples**
  - Store objects inside of nested containers
  - Transplantable
    - Computer → Controller
    - Controller → Controller
  - No pointers to fix up

# Memory images

- **p14p, eLua use dynamic loaders**
  - Objects copied from flash to RAM
- **Owl uses memory images**
  - Can stay in flash, not SRAM
  - 512KB flash vs. 96KB SRAM
- **Results**
  - 4x reduced SRAM footprint

# Calling C library functions

- **C is a necessary evil**
  - Peripheral I/O libraries
    - Generally vendor provided
    - Must provide a way for Python to call C
- **Two techniques compared**
  - Automatically expose functions from .h file
  - Trade-offs in space and speed

# Calling C library functions

- **User cannot directly control execution**
  - In an interpreter loop
  - Need some way to let programmer break out of loop

```
bytecode = *IP;
switch bytecode:
    case BINARY_ADD:
        // add two Python ints
        // together
        IP++;

case JUMP:
    // change IP

case CALL_FUNCTION:
    // create new frame
    // change IP to new frame
```

# Calling C library functions

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case CALL_FUNCTION:
    if (func_name == "uart_init") {
        call_uart_init();
    }
    else {
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    }
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# Calling C library functions

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    case CALL_FUNCTION:
        if (func_name == "uart_init") {
            call_uart_init();
        }
        else if (func_name == "uart_send") {
            call_uart_send();
        }
        else {
            // create new frame
            // change IP to new frame
        }
```

# call_uart_init()

```
/* Variable declarations */
PmReturn_t retval = PM_RET_OK;
pPmObj_t p0;
uint32_t peripheral;

/* If wrong number of arguments, raise TypeError */
if (NATIVE_GET_NUM_ARGS() != 1)  {
  PM_RAISE(retval, PM_RET_EX_TYPE);
  return retval;
}

/* Get Python argument */
p0 = NATIVE_GET_LOCAL(0);

/* If wrong argument type, raise TypeError */
if (OBJ_GET_TYPE(p0) != OBJ_TYPE_INT)  {
  PM_RAISE(retval, PM_RET_EX_TYPE);
  return retval;
}

/* Convert Python argument to C argument */
peripheral = ((pPmInt_t)p0)->val;

/* Actual call to native function */
SysCtlPeripheralEnable(peripheral);

/* Return Python object */
NATIVE_SET_TOS(PM_NONE);
return retval;
```

- **Wrappers for functions**
  - Interpreter calls wrapper
  - Wrapper converts arguments
  - Calls function
  - Wrapper converts result
  - Returns result on stack
- **Call C as you call Python**

# Calling C library functions

```
import gpio

class Output:
    def __init__(self, portpin):
        self.port = PORTS[portpin[0]]
        self.pin = PINS[portpin[1]]

        # turn on GPIO module
        init_port(portpin[0])

        # configure pin for output
        gpio.GPIOPinTypeGPIOOutput(self.port, self.pin)

    def write(self, value):
        if value:
            # turn pin on
            gpio.GPIOPinWrite(self.port, self.pin, self.pin)
        else:
            # turn pin off
            gpio.GPIOPinWrite(self.port, self.pin, 0)
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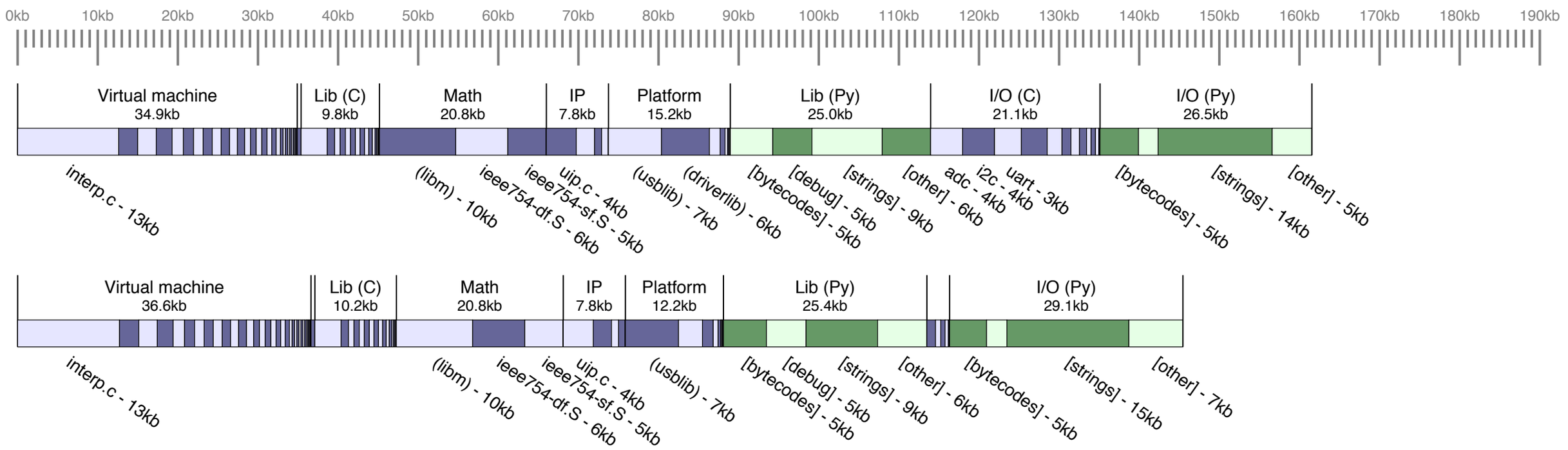
```

- **Wrapped functions**
  - Manually write wrappers
    - p14p, eLua
  - Autowrapping
    - Similar to SWIG
- **Simple**
  - Any compiler
  - Any architecture
  - Lots of duplicated code

# Foreign Function Interface

- **Based on libffi**
  - Calls C functions with arbitrary signature
  - Implements calling convention
    - Custom port to Cortex-M3
- **eFFI**
  - Functions statically linked into program
  - Function pointer tables instead of DWARF symbol headers
    - Compatible with statically linked embedded system
  - No duplicated code

# Comparison




- **eFFI smaller**
  - VM 2KB larger
  - Eliminates 21KB of wrappers
- **Wrapper functions simpler**
  - 2x faster, largely irrelevant in practice

# Owl: A Development Environment for Microcontrollers

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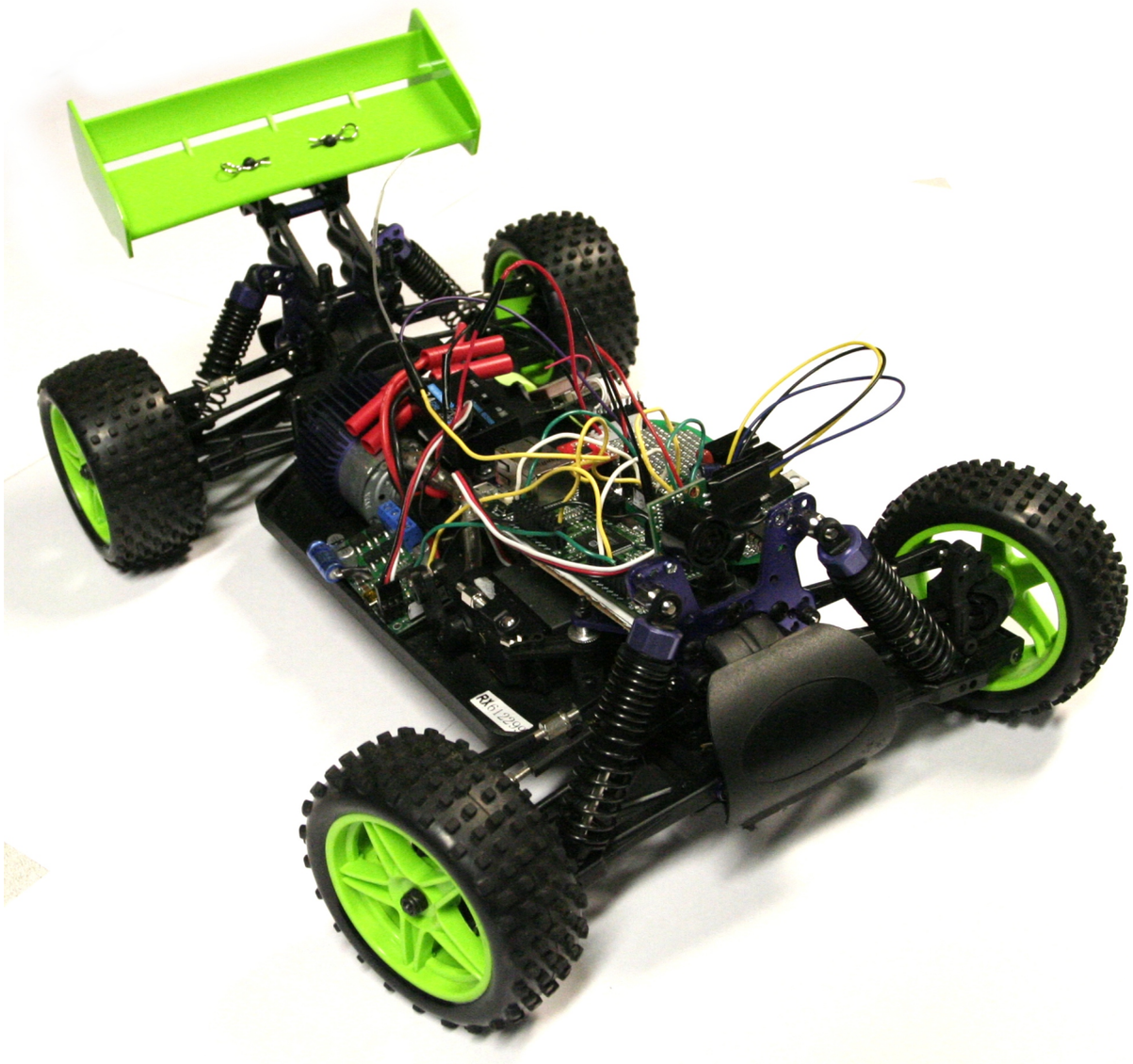
- **Yes, you can run a managed run-time on a microcontroller.**
- **It works, right now.**
  - Autonomous car
  - Toys
  - Courseware
    - ENGI128 at Rice
  - Cookware
  - …



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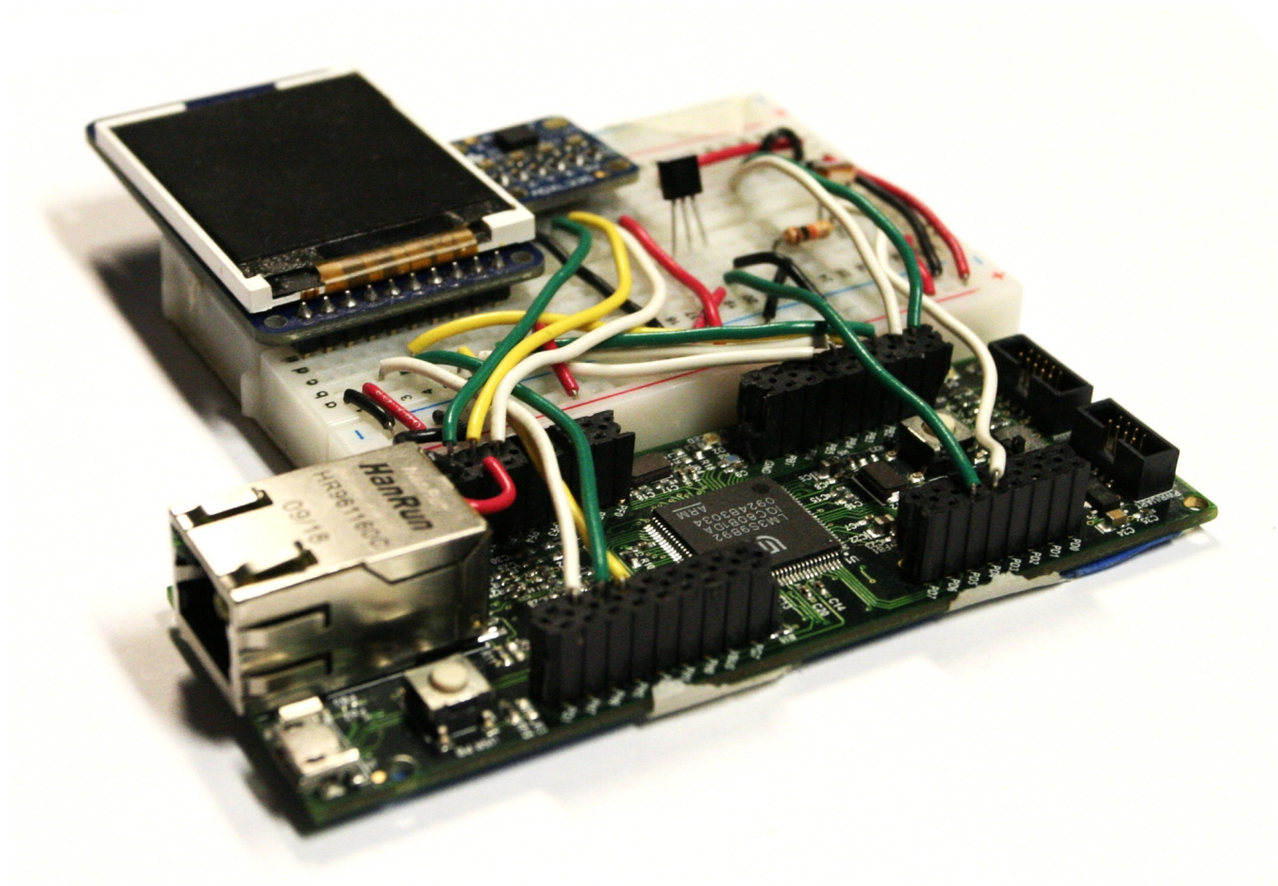

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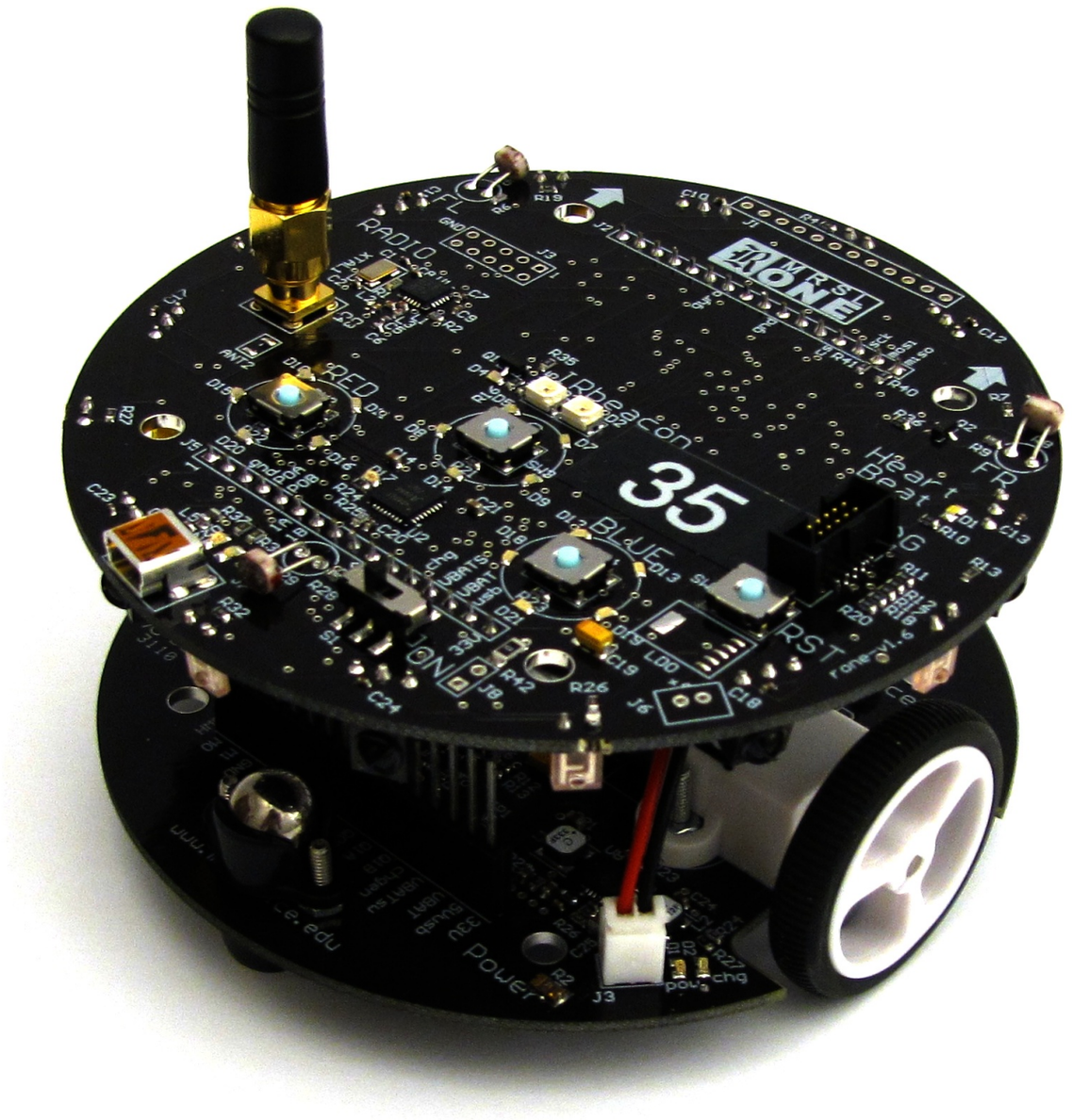
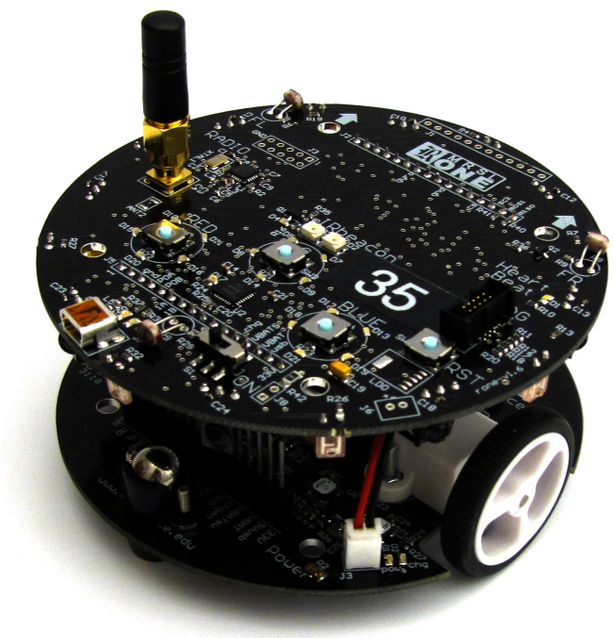
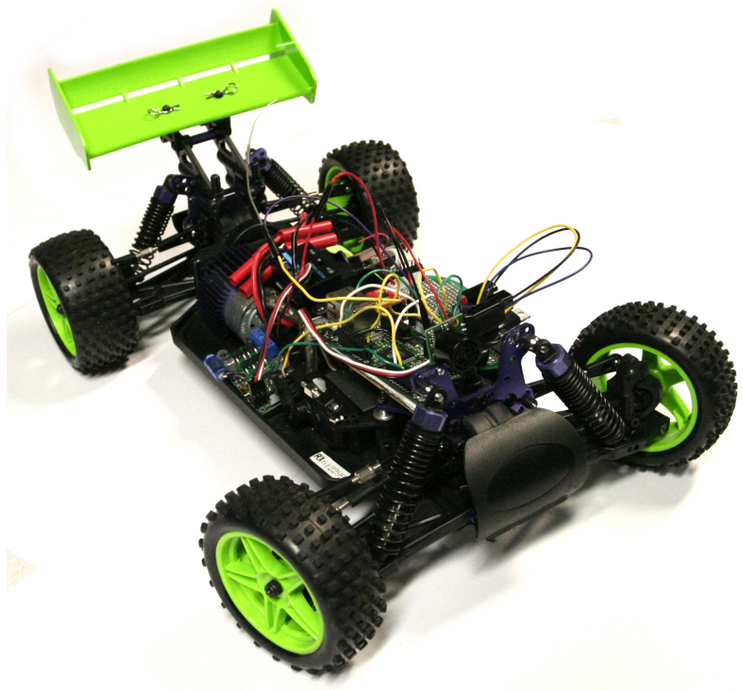


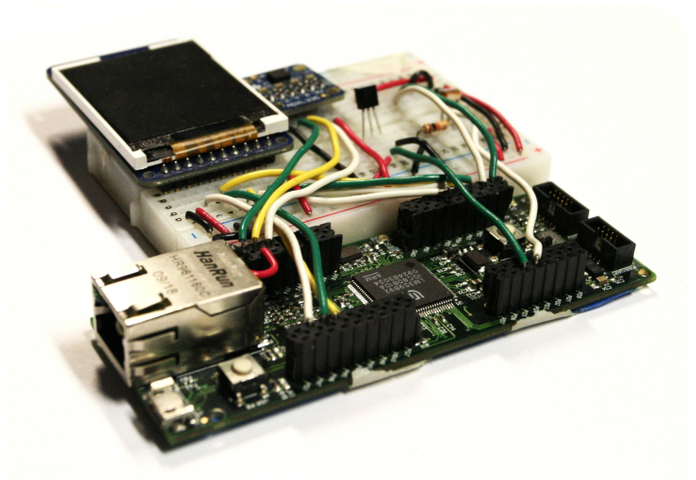
# Owl: A Development Environment for Microcontrollers

- **Interesting area for research**
  - Two innovations presented here
  - More in paper
  - Far more in the future?
    - Compare to C?
    - To MATLAB?
- **Vital area for research**
  - Microcontrollers are getting more common
  - Larger peripheral set is making programming harder
    - We can and **must** reverse this trend

# Owl: A Development Environment for Microcontrollers







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