Physics 120B: Lecture 4

Under the Arduino Hood

Arduino Makes it Look Easy

- High-level functions remove user/programmer from processor details
  - on the plus side, this means you can actually get things done without a steep learning curve
  - on the down side, you don't understand fundamentally what your actions are doing…
  - …or how to take advantage of processor capabilities that are not wrapped into high-level functions
- So today, we'll look a bit into what Arduino is *actually* doing—to a limited extent!

Where Do the Monsters Lurk?

- What I will call the root directory is at:
  - On a Mac:
    - /Applications/Arduino.app/Contents/Resources/Java/hardware/arduino/
  - On Windows:
    - Arduino-Install-Directory/Hardware/Arduino/
  - On Linux:
    - (likely) /usr/share/arduino/
    - also may check /usr/local/
- I'll describe contents as found on the Mac
  - it's what I have
  - hopefully is reasonably universal

Contents of root directory

- On my Mac, the aforementioned directory has:

```
boards.txt      cores/          programmers.txt
bootloaders/    firmwares/      variants/
```

  - `boards.txt` has specific info for the various Arduino boards
- `cores`/ has only a directory called `arduino`/, which we will investigate later
- `bootloaders`/ has

```
atmega/   atmega8/  bt/      caterina/ lilypad/  optiboot/ stk500v2/
```

- `variants`/ has

```
eightanaloginputs/ leonardo/        mega/              standard/
```

  - each of which contains a single file: `pins_arduino.h`
  - maps pinouts of specific devices

File Types in "Standard" C Programming

- Source Code
  - the stuff you type in: has `.c` extension, or `.cpp` for C++
- Compiled "Executable"
  - the ready-to-run product: usually no extension in Unix/ Mac, `.exe` in DOS
- Header Files
  - contain definitions of useful functions, constants: `.h` extension
- Object Files
  - a pre-linked compiled tidbit: `.o` in Unix, `.obj` in DOS
  - only if you're building in pieces and linking later

In root/cores/arduino/

- Here's what I show, broken out by extension
  - I have 36 files total in this directory, all `.c`, `.cpp`, or `.h`
- First, 6 C files:

```
mojo:arduino$ wc *.c
     298    1116    8198 WInterrupts.c
     324    1468    9394 wiring.c
     282    1133    7374 wiring_analog.c
     178     668    4931 wiring_digital.c
      69     416    2643 wiring_pulse.c
      55     236    1601 wiring_shift.c
```

- The `wc` function means word count
  - returns number of lines, # of words, # of characters for each file

Directory, continued

- Now, 12 C++ files:

```
mojo:arduino$ wc *.cpp
     233     896    6718 CDC.cpp
     519    1677   13772 HID.cpp
     428    1442   11400 HardwareSerial.cpp
      56     115    1152 IPAddress.cpp
     263     798    5216 Print.cpp
     270    1137    7277 Stream.cpp
     601    1783   14311 Tone.cpp
     672    1734   13134 USBCore.cpp
      59     265    1649 WMath.cpp
     645    1923   14212 WString.cpp
      20      22     202 main.cpp
      18      41     325 new.cpp
```

- Note in particular main.cpp: 20 lines of fun
  - we'll look at in a bit

Header files

- Finally, the 18 header files

```
mojo:arduino$ wc *.h
     215     677    5690 Arduino.h
      26      97     697 Client.h
      81     289    2363 HardwareSerial.h
      76     419    2978 IPAddress.h
      23      42     401 Platform.h
      78     328    2462 Print.h
      40     207    1332 Printable.h
       9      17     111 Server.h
      96     584    4005 Stream.h
     194     478    5224 USBAPI.h
     302     846    7855 USBCore.h
      63     236    1872 USBDesc.h
      88     691    4180 Udp.h
     167     699    4576 WCharacter.h
     205    1151    8470 WString.h
     515    1535   10379 binary.h
      22      62     562 new.h
      69     230    1752 wiring_private.h
```

- We'll look at Arduino.h next

Arduino.h

- Contains function prototypes, definition of constants, some useful algorithms
- Excerpts follow

```
#include <stdlib.h>
#include <string.h>
#include <math.h>

#include <avr/pgmspace.h>
#include <avr/io.h>
#include <avr/interrupt.h>

#include "binary.h"
```

- These are standard C libraries that are being pulled in
  - note in particular that the math library is automatically used

Arduino.h, continued

- Now we have some constants defined
  - recall, `#define` acts as text replacement

```
#define HIGH 0x1
#define LOW  0x0

#define INPUT 0x0
#define OUTPUT 0x1
#define INPUT_PULLUP 0x2

#define true 0x1
#define false 0x0

#define PI 3.14159265358979323846264338327950
#define HALF_PI 1.57079632679489661923132169163980
#define TWO_PI 6.28318530717958647692528676655900
#define DEG_TO_RAD 0.017453292519943295769236907684886
#define RAD_TO_DEG 57.295779513082320876798154814105
```

- In some cases, to absurd precision!

Arduino.h, continued

- The `#define` construct can also create useful functions

```
#define min(a,b) ((a)<(b)?(a):(b))
#define max(a,b) ((a)>(b)?(a):(b))
#define abs(x) ((x)>0?(x):-(x))
#define constrain(amt,lo,hi) ((amt)<(lo)?(lo):((amt)>(hi)?(hi):(amt)))
#define round(x)     ((x)>=0?(long)((x)+0.5):(long)((x)-0.5))
#define radians(deg) ((deg)*DEG_TO_RAD)
#define degrees(rad) ((rad)*RAD_TO_DEG)
#define sq(x) ((x)*(x))

#define lowByte(w) ((uint8_t) ((w) & 0xff))
#define highByte(w) ((uint8_t) ((w) >> 8))

#define bitRead(value, bit) (((value) >> (bit)) & 0x01)
#define bitSet(value, bit) ((value) |= (1UL << (bit)))
#define bitClear(value, bit) ((value) &= ~(1UL << (bit)))
#define bitWrite(val, bit, bval) (bval ? bitSet(val, bit) : bitClear
(val, bit))
```

- Some labels shortened to fit on this slide (hi, lo, etc.)

Arduino.h, continued

- Also included are function prototypes
  - so that we know what types are expected in function calls

```
typedef uint8_t byte;          // 8-bit integer, same as char

void pinMode(uint8_t, uint8_t);
void digitalWrite(uint8_t, uint8_t);
int digitalRead(uint8_t);
int analogRead(uint8_t);
void analogReference(uint8_t mode);
void analogWrite(uint8_t, int);

unsigned long millis(void);
unsigned long micros(void);
void delay(unsigned long);

void setup(void);
void loop(void);
```

- This is just an excerpt, for familiar functions

root/variants/standard/pins_arduino.h

- maps pins to functions—excerpts:

```
#define NUM_DIGITAL_PINS            20
#define NUM_ANALOG_INPUTS           6
#define analogInputToDigitalPin(p)  ((p < 6) ? (p) + 14 : -1)

// ATMEL ATMEGA8 & 168 / ARDUINO
//
//                   +-\/-+
//             PC6  1|    |28  PC5 (AI 5)
//       (D 0) PD0  2|    |27  PC4 (AI 4)
//       (D 1) PD1  3|    |26  PC3 (AI 3)
//       (D 2) PD2  4|    |25  PC2 (AI 2)
// PWM+ (D 3) PD3  5|    |24  PC1 (AI 1)
//       (D 4) PD4  6|    |23  PC0 (AI 0)
//             VCC  7|    |22  GND
//             GND  8|    |21  AREF
//             PB6  9|    |20  AVCC
//             PB7 10|    |19  PB5 (D 13)
// PWM+ (D 5) PD5 11|    |18  PB4 (D 12)
// PWM+ (D 6) PD6 12|    |17  PB3 (D 11) PWM
//       (D 7) PD7 13|    |16  PB2 (D 10) PWM
//       (D 8) PB0 14|    |15  PB1 (D 9) PWM
//                   +----+
```

root/cores/arduino/main.cpp

- Simple: initialize, run your setup, start infinite loop and run your loop, keeping a lookout for serial comm

```
#include <Arduino.h>

int main(void)
{
        init();

#if defined(USBCON)
        USBDevice.attach();
#endif

        setup();

        for (;;) {
                loop();
                if (serialEventRun) serialEventRun();
        }

        return 0;
}
```

Finally, root/boards.txt

- Examples for Uno and Nano

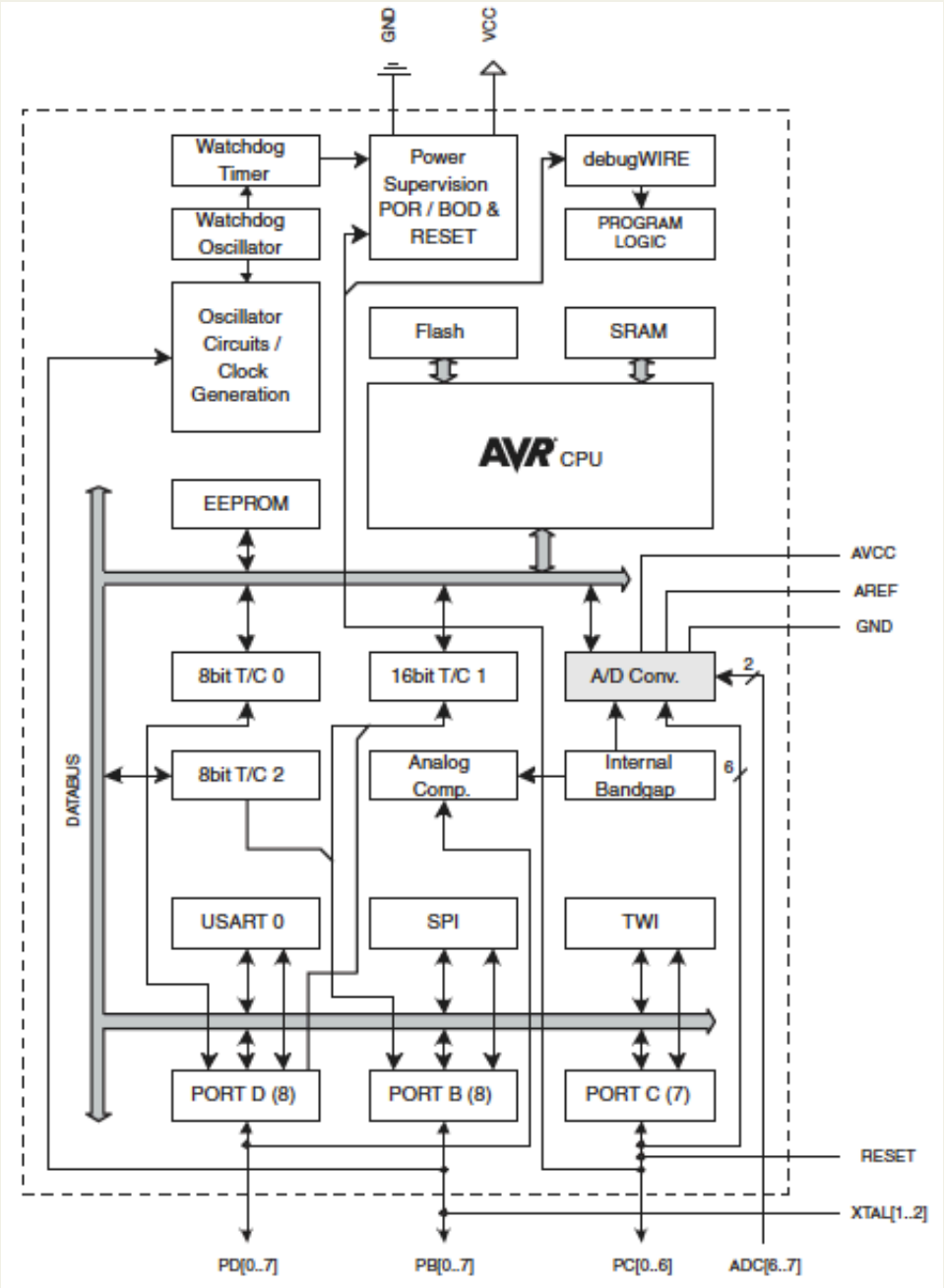
```
uno.name=Arduino Uno
uno.upload.protocol=arduino
uno.upload.maximum_size=32256
uno.upload.speed=115200
uno.bootloader.low_fuses=0xff
uno.bootloader.high_fuses=0xde
uno.bootloader.extended_fuses=0x05
uno.bootloader.path=optiboot
uno.bootloader.file=
    optiboot_atmega328.hex
uno.bootloader.unlock_bits=0x3F
uno.bootloader.lock_bits=0x0F
uno.build.mcu=atmega328p
uno.build.f_cpu=16000000L
uno.build.core=arduino
uno.build.variant=standard
```

```
nano328.name=Arduino Nano w/ ATmega328

nano328.upload.protocol=arduino
nano328.upload.maximum_size=30720
nano328.upload.speed=57600

nano328.bootloader.low_fuses=0xFF
nano328.bootloader.high_fuses=0xDA
nano328.bootloader.extended_fuses=0x05
nano328.bootloader.path=atmega
nano328.bootloader.file=
    ATmegaBOOT_168_atmega328.hex
nano328.bootloader.unlock_bits=0x3F
nano328.bootloader.lock_bits=0x0F

nano328.build.mcu=atmega328p
nano328.build.f_cpu=16000000L
nano328.build.core=arduino
nano328.build.variant=eightanaloginputs
```

- Note core, variant
  - and CPU speed 16 MHz

But the Rabbit Hole Goes Much Farther

- Underneath it all is a microprocessor with staggering complexity
  - full datasheet (avail via course website) is 567 pages
  - summary datasheet (strongly encourage perusal) is 35 pp.
- Note in particular in the summary datasheet:
  - p. 2 the Uno uses the 28-pin PDIP (upper right)
  - read the port descriptions on pp. 3–4, even if foreign
  - block diagram p. 5
  - register map pp. 7–12
  - assembly instruction set pp. 13–15
  - can safely ignore pp. 16–35 ;-)


GND
VCC
Watchdog Timer
Watchdog Oscillator
Power Supervision POR / BOD & RESET
debugWIRE
PROGRAM LOGIC
Oscillator Circuits / Clock Generation
Flash
SRAM
AVR CPU
EEPROM
AVCC
AREF
GND
8bit T/C 0
16bit T/C 1
A/D Conv.
2
8bit T/C 2
Analog Comp.
Internal Bandgap
6
DATABUS
USART 0
SPI
TWI
PORT D (8)
PORT B (8)
PORT C (7)
RESET
XTAL[1..2]
PD[0..7]
PB[0..7]
PC[0..6]
ADC[6..7]

Assignments/Announcements

- Absorb as much as possible from the summary datasheet
- Interested in feedback on labs, since this is first pass
  - usefulness
  - clarity
  - completeness on topic
  - missing bits
  - excessive bits