Low-Level C Programming

CSEE W4840

Prof. Stephen A. Edwards

Columbia University
Goals

Function is correct
Source code is concise, readable, maintainable
Time-critical sections of program run fast enough
Object code is small and efficient

Basically, optimize the use of three resources:

- Execution time
- Memory
- Development/maintenance time
Like Writing English

You can say the same thing many different ways and mean the same thing.

There are many different ways to say the same thing.

The same thing may be said different ways.

There is more than one way to say it.

Many sentences are equivalent.

Be succinct.
Arithmetic

Integer Arithmetic                     Fastest

Floating-point arithmetic in hardware   Slower

Floating-point arithmetic in software   Very slow

\[
\begin{align*}
+,- \\
\times \\
\div \\
\text{sqrt, sin, log, etc.}
\end{align*}
\]
Simple benchmarks

```c
for (i = 0 ; i < 10000 ; ++i)
    /* arithmetic operation */
```

On my desktop Pentium 4 with good hardware floating-point support,

<table>
<thead>
<tr>
<th>Operator</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (int)</td>
<td>1</td>
</tr>
<tr>
<td>* (int)</td>
<td>5</td>
</tr>
<tr>
<td>/ (int)</td>
<td>12</td>
</tr>
<tr>
<td>&lt;&lt; (int)</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operator</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (double)</td>
<td>5</td>
</tr>
<tr>
<td>* (double)</td>
<td>5</td>
</tr>
<tr>
<td>/ (double)</td>
<td>10</td>
</tr>
<tr>
<td>sqrt</td>
<td>28</td>
</tr>
<tr>
<td>sin</td>
<td>48</td>
</tr>
<tr>
<td>pow</td>
<td>275</td>
</tr>
</tbody>
</table>
Simple benchmarks

On my Zaurus SL 5600, a 400 MHz Intel PXA250 Xscale (ARM) processor:

<table>
<thead>
<tr>
<th>Operator</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ (int)</td>
<td>1</td>
</tr>
<tr>
<td>* (int)</td>
<td>1</td>
</tr>
<tr>
<td>/ (int)</td>
<td>7</td>
</tr>
<tr>
<td>&lt;&lt; (int)</td>
<td>1</td>
</tr>
<tr>
<td>+ (double)</td>
<td>140</td>
</tr>
<tr>
<td>* (double)</td>
<td>110</td>
</tr>
<tr>
<td>/ (double)</td>
<td>220</td>
</tr>
<tr>
<td>sqrt</td>
<td>500</td>
</tr>
<tr>
<td>sin</td>
<td>3300</td>
</tr>
<tr>
<td>pow</td>
<td>820</td>
</tr>
</tbody>
</table>
Operations on `char`, `short`, `int`, and `long` probably run at the same speed (same ALU).

Same for `unsigned` variants

`int` or `long` slower when they exceed machine’s word size.

Operations on `floats` performed in double precision. `float` only useful for reducing memory.
Arithmetic Lessons

Try to use integer addition/subtraction

Avoid multiplication unless you have hardware

Avoid division

Avoid floating-point, unless you have hardware

Really avoid math library functions
C has many bit-manipulation operators.

- Bit-wise AND ($\&$)
- Bit-wise OR ($|$)
- Bit-wise XOR ($\^$)
- Negate (one’s complement) ($\sim$)
- Right-shift ($>>$)
- Left-shift ($<<$)

Plus assignment versions of each.
Bit-maneipulation basics

```c
a |= 0x4;       /* Set bit 2 */
b &= ~0x4;      /* Clear bit 2 */
c &= ~(1 << 3); /* Clear bit 3 */
d ^= (1 << 5);  /* Toggle bit 5 */
e >>= 2;        /* Divide e by 4 */
```
/* Set \( b \) to the rightmost 1 in \( a \) */
b = a & (a ^ (a - 1));

/* Set \( d \) to the number of 1’s in \( c \) */
char c, d;
d = (c & 0x55) + ((c & 0xaa) >> 1);
d = (d & 0x33) + ((d & 0xcc) >> 2);
d = (d & 0x0f) + ((d & 0xf0) >> 4);
Faking Multiplication

Addition, subtraction, and shifting are fast. Can sometimes supplant multiplication. Like floating-point, not all processors have a dedicated hardware multiplier. Recall the multiplication algorithm from elementary school, but think binary:

\[
\begin{array}{c}
101011 \\
\times 1101 \\
\hline
101011 \\
10101100 \\
+101011000 \\
\hline
1000101111
\end{array}
\]

\[= 43 + 43 \ll 2 + 43 \ll 3 = 559\]
Faking Multiplication

Even more clever if you include subtraction:

\[
\begin{array}{c}
101011 \\
\times \ 1110 \\
\hline
1010110 \\
10101100 \\
+101011000 \\
\hline
1001011010
\end{array}
\]

\[= 43 \ll 1 + 43 \ll 2 + 43 \ll 3\]

\[= 43 \ll 4 - 43 \ll 2\]

\[= 602\]

Only useful

- for multiplication by a constant
- for “simple” multiplicands
- when hardware multiplier not available
Faking Division

Division is a much more complicated algorithm that generally involves decisions. However, division by a power of two is just a shift:

\[
a / 2 = a >> 1
\]
\[
a / 4 = a >> 2
\]
\[
a / 8 = a >> 3
\]

There is no general shift-and-add replacement for division, but sometimes you can turn it into multiplication:

\[
a / 1.33333333
\]
\[
= a * 0.75
\]
\[
= a * 0.5 + a * 0.25
\]
\[
= a >> 1 + a >> 2
\]
Multi-way branches

```c
if (a == 1)
    foo();
else if (a == 2)
    bar();
else if (a == 3)
    baz();
else if (a == 4)
    qux();
else if (a == 5)
    quux();
else if (a == 6)
    corge();

switch (a) {
    case 1:
        foo(); break;
    case 2:
        bar(); break;
    case 3:
        baz(); break;
    case 4:
        qux(); break;
    case 5:
        quux(); break;
    case 6:
        corge(); break;
}
```
Microblaze code for if-then-else

lwi  r3, r19, 44  # fetch "a" from stack
addik r18, r0, 1  # load constant 1
cmp  r18, r18, r3  # compare with "a"
bnei r18, $L3  # skip if not equal
brlid r15, foo  # call foo
nop  # delay slot
bri $L4  # branch to end

$L3:
lwi  r3, r19, 44  # fetch "a" from stack
addik r18, r0, 2  # load constant 2
cmp  r18, r18, r3  # compare with "a"
bnei r18, $L5  # skip if not equal
brlid r15, bar  # call bar
nop  # delay slot
bri $L4  # branch to end

$L5:
```assembly
addik r3, r22, -1
xori r18, r3, 5
bgei r18, $L0
blti r3, $L14  # Skip if less than 1
bri $L1
$L0:
    rsubik r18, r3, 5
    blti r18, $L14  # Skip if greater than 6
$L1:
    addk r3, r3, r3  # Multiply by four
    addk r3, r3, r3
    lw1 r3, r3, $L21  # Fetch address from table
    bra r3  # Branch to a case label
.sdata2
$L21:  # Branch table
    .gpword $L15
    .gpword $L16
    .gpword $L17
    .gpword $L18
    .gpword $L19
    .gpword $L20
```
.text
$L15:          # case 1:
  brlid  r15,foo
  nop
  bri  $L14
$L16:          # case 2:
  brlid  r15,bar
  nop
  bri  $L14
$L17:          # case 3:
  brlid  r15,baz
  nop
  bri  $L14
$L18:          # case 4:
  brlid  r15,qux
  nop
  bri  $L14
$L19:          # case 5:
  brlid  r15,quux
  nop
  bri  $L14
There are many ways to compute a “random” function of one variable:

```c
/* OK, especially for sparse domain */
if (a == 0) x = 0;
else if (a == 1) x = 4;
else if (a == 2) x = 7;
else if (a == 3) x = 2;
else if (a == 4) x = 8;
else if (a == 5) x = 9;
```
/* Better for large, dense domains */
switch (a) {
case 0: x = 0; break;
case 1: x = 4; break;
case 2: x = 7; break;
case 3: x = 2; break;
case 4: x = 8; break;
case 5: x = 9; break;
}

/* Best: constant-time lookup table */
int f[] = {0, 4, 7, 2, 8, 9};
x = f[a]; /* assumes 0 <= a <= 5 */
Modern processors, especially RISC, strive to make this cheap. Arguments passed through registers. Still has noticeable overhead.

Calling, entering, and returning on the Microblaze:

```c
int foo(int a, int b) {
    int c = bar(b, a);
    return c;
}
```
foo:

    # Function prologue:
    addik r1, r1, -40  # Update frame pointer
    sw r15, r0, r1    # Save calling address (r15)
    add r3, r5, r0    # Swap r5 (a) and r6 (b)
    add r5, r6, r0    # using r3 as temp
    brlid r15, bar    # call bar()
    add r6, r3, r0    # delay slot: executes before

    # Function epilog:
    lw r15, r0, r1    # retrieve return address
    rtsd r15, 8       # return to caller
    addik r1, r1, 40  # delay slot: release frame
Why multiply when you can add?

```c
struct {
    int a;
    char b;
    int c;
} foo[10];
int i;
for (i=0 ; i<10 ; ++i) {
    foo[i].a = 77;
    foo[i].b = 88;
    foo[i].c = 99;
}
```

```c
struct {
    int a;
    char b;
    int c;
} *fp, *fend, foo[10];
fend = foo + 10;
for (fp = foo ; fp != fend ; ++fp) {
    fp->a = 77;
    fp->b = 88;
    fp->c = 99;
}
```

Good optimizing compilers do this automatically.
$L3:$
  lwi  r3, r19, 28  # fetch i from stack
  addik r18, r0, 9
  cmp  r18, r18, r3
  blei r18, $L6
  bri $L4  # exit if i > 9

$L6:$
  lwi  r5, r19, 28  # fetch i from stack
  addik r6, r0, 12  # compute i * 12
  brlid r15, mulsi3_proc
  nop
  addik r4, r0, foo
  addk r3, r4, r3  # foo + i * 12
  addik r4, r0, 77
  sw r4, r0, r3  # foo[i].a = 77
  lwi  r5, r19, 28  # fetch i from stack
  addik r6, r0, 12  # compute i * 12
  brlid r15, mulsi3_proc
  nop
  addik r4, r0, foo  # foo + i * 12
  addk r3, r3, r4
  addik r4, r0, 88
  sbi r4, r3, 4  # foo[i].b = 88
Unoptimized pointer code (fragment)

$L8:
  lw    r3, r0, r19
  lwi   r4, r19, 4
  rsubk r18, r4, r3  # fp == fend?
  bnei  r18, $L11
  bri   $L9
$L11:
  lw    r3, r0, r19
  addik r4, r0, 77
  sw    r4, r0, r3  # fp->a = 77
  lw    r3, r0, r19
  addik r4, r0, 88
  sbi   r4, r3, 4   # fp->b = 88
  lw    r3, r0, r19
  addik r4, r0, 99
  swi   r4, r3, 8   # fp->c = 99
  lw    r3, r0, r19
  addik r4, r3, 12
  sw    r4, r0, r19  # ++fp (stacked)
  bri   $L8
$L9:
Optimized array code

addik r4,r0,foo  # get address of foo
addik r6,r0,77   # save constant
addik r5,r4,108  # r5 has end of array
$L6:
  addik r3,r0,88
  sbi  r3,r4,4   # foo[i].b = 88
  addik r3,r0,99
  sw   r6,r0,r4  # foo[i].a = 77
  swi  r3,r4,8   # foo[i].c = 99
  addik r4,r4,12 # next array element
  cmp  r18,r5,r4 # hit foo[10]?
  blei r18,$L6
addik  r4, r0, foo+120  # fend = foo + 10
addik  r3, r4, -120    # fp = foo
rsubk  r18, r4, r3     # fp == fend?
beqi   r18, $L14       # never taken
addik  r7, r0, 77      # load constants
addik  r6, r0, 88      # load constants
addik  r5, r0, 99      # load constants
$L12:
sbi    r6, r3, 4        # fp->b = 88
sw     r7, r0, r3       # fb->a = 77
swi    r5, r3, 8        # fb->c = 99
addik  r3, r3, 12      # ++fp
rsubk  r18, r4, r3     # fp == fend?
bnei   r18, $L12       # never taken
$L14:
rtsd   r15, 8          # return
nop
How much time does the following loop take?

```c
for ( i = 0 ; i < 1024 ; ++i) a += b[i];
```

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cycles per iteration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Memory read</td>
<td>2 or 7</td>
</tr>
<tr>
<td>Addition</td>
<td>1</td>
</tr>
<tr>
<td>Loop overhead</td>
<td>( \approx 4 )</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6–12</strong></td>
</tr>
</tbody>
</table>

The Microblaze runs at 50 MHz, one instruction per cycle, so this takes

\[
6 \cdot 1024 \cdot \frac{1}{50 \text{MHz}} = 0.12 \mu s \quad \text{or} \quad 12 \cdot 1024 \cdot \frac{1}{50 \text{MHz}} = 0.24 \mu s
\]
Double-checking

GCC generates great code with `–O7`:

```c
sumarray:
  addik      r1,r1,-24  # create frame
  add        r4,r0,r0  # a = 0
  addik      r6,r5,4092 # end of array

$L6$:  # cycles
  lw         r3,r0,r5  # b[i]   2-7
  addik      r5,r5,4  # ++i    1
  addk       r4,r4,r3  # a += b[i] 1
  cmp        r18,r6,r5 # i < 1024 1
  blei       r18,$L6   3

  add        r3,r4,r0  # return a
  rtsd       r15,8
  addik      r1,r1,24  # release frame
```
## Features in order of increasing cost

1. Integer arithmetic
2. Pointer access
3. Simple conditionals and loops
4. Static and automatic variable access
5. Array access
6. Floating-point with hardware support
7. Switch statements
8. Function calls
9. Floating-point emulation in software
10. `malloc()` and `free()`
11. Library functions (sin, log, printf, etc.)
12. Operating system calls (open, sbrk, etc.)
/* fixed address: visible to other files */
int global_static;
/* fixed address: only visible within file */
static int file_static;

/* parameters always stacked */
int foo(int auto_param)
{
    /* fixed address: only visible to function */
    static int func_static;
    /* stacked: only visible to function */
    int auto_i, auto_a[10];
    /* array explicitly allocated on heap */
    double *auto_d =
        malloc(sizeof(double)*5);

    /* return value in register or stacked */
    return auto_i;
}
Dynamic Storage Allocation

↓ `free()`

↓ `malloc()`
Dynamic Storage Allocation

Rules:

Each allocated block contiguous (no holes)
Blocks stay fixed once allocated

`malloc()`

Find an area large enough for requested block
Mark memory as allocated

`free()`

Mark the block as unallocated
Simple Dynamic Storage Allocation

Maintaining information about free memory

Simplest: Linked list

The algorithm for locating a suitable block

Simplest: First-fit

The algorithm for freeing an allocated block

Simplest: Coalesce adjacent free blocks
Dynamic Storage Allocation

\[
\downarrow \text{malloc( )}
\]
Simple Dynamic Storage Allocation

↓ free()
On most processors, access to automatic (stacked) data and globals is equally fast.

Automatic usually preferable since the memory is reused when function terminates.

Danger of exhausting stack space with recursive algorithms. Not used in most embedded systems.

The heap (malloc) should be avoided if possible:

- Allocation/deallocation is unpredictably slow
- Danger of exhausting memory
- Danger of fragmentation

Best used sparingly in embedded systems
“Magical” memory locations that, when written or read, send or receive data from hardware. Hardware that looks like memory to the processor, i.e., addressable, bidirectional data transfer, read and write operations.

Does not always behave like memory:

- Act of reading or writing can be a trigger (data irrelevant)
- Often read- or write-only
- Read data often different than last written
With the Microblaze

Xilinx supplies a library of I/O operations:
#include "xbasic_types.h"
#include "xio.h"

XIo_In8(XIo_Address address)
XIo_In16(XIo_Address address)
XIo_In32(XIo_Address address)
void XIo_Out8(XIo_Address address, Xuint8 data)
void XIo_Out16(XIo_Address address, Xuint16 data)
void XIo_Out32(XIo_Address address, Xuint32 data)

Each is a simple macro, e.g.,
#define XIo_Out32(Addr, Value) \  
{ (*(volatile Xuint32 *)(Addr) = Value); } 
volatile warns compiler not to optimize it
#include "xbasic_types.h"
#include "xio.h"

int main()
{
    int i, j;
    print("Hello World!\r\n");
    
    for(j=0; j<256; j++)
        for(i=0; i<100000; i++) {
            XIo_Out32(0xFEFF0200, j<<24);
            XIo_Out32(0xFEFF0204, j<<24);
            XIo_Out32(0xFEFF0208, j<<24);
            XIo_Out32(0xFEFF020C, j<<24);
        }
    print("Goodbye\r\n");
    return 0;
}
Memory-mapped I/O puts the processor in charge: only it may initiate communication.

Typical operation:

- Check hardware conditions by reading “status registers”
- When ready, send next “command” by writing control and data registers
- Check status registers for completion, waiting if necessary

Waiting for completion: “polling”

“Are we there yet?” “No.” “Are we there yet?” “No” “Are we there yet?” “No” “Are we there yet?” “No”
Idea: have hardware initiate communication when it wants attention.

Processor responds by immediately calling an interrupt handling routine, suspending the currently-running program.
Unix Signals

The Unix environment provides “signals,” which behave like interrupts.

```c
#include <stdio.h>
#include <signal.h>

void handleint() {
    printf("Got an INT\n");
    /* some variants require this */
    signal(SIGINT, handleint);
}

int main() {
    /* Register signal handler */
    signal(SIGINT, handleint);
    /* Do nothing forever */
    for (;;) { }
    return 0;
}
```
#include "xbasic_types.h"
#include "xio.h"
#include "xintc_l.h"
#include "xuartlite_l.h"
#include "xparameters.h"

int main()
{
    XIntc_RegisterHandler( XPAR_INTC_BASEADDR, XPAR_MYUART_DEVICE_ID,
                            (XInterruptHandler)uart_handler, (void *)0);
    XIntc_mEnableIntr(XPAR_INTC_BASEADDR,
                      XPAR_MYUART_INTERRUPT_MASK);
    XIntc_mMasterEnable(XPAR_INTC_BASEADDR);
    XIntc_Out32(XPAR_INTC_BASEADDR + XPAR_INTC_BASEADDR +
                XPAR_INTC_INTERRUPT_OFFSET,
                XPAR_INT_MASTER_ENABLE_MASK);
    microblaze_enable_interrupts();
    XUartLite_mEnableIntr(XPAR_MYUART_BASEADDR);
}
#include "xbasic_types.h"
#include "xio.h"
#include "xparameters.h"
#include "xuartlite_l.h"

void uart_handler(void *callback)
{
    Xuint32 IsrStatus;
    Xuint8 incoming_character;
    IsrStatus = XIo_In32(XPAR_MYUART_BASEADDR + XUL_STATUS_REG_OFFSET);
    if ((IsrStatus & (XUL_SR_RX_FIFO_FULL |
                     XUL_SR_RX_FIFO_VALID_DATA)) != 0) {
        incoming_character = (Xuint8) XIo_In32(XPAR_MYUART_BASEADDR +
                                              XUL_RX_FIFO_OFFSET);
    }
    if ((IsrStatus & XUL_SR_TX_FIFO_EMPTY) != 0)
        /* output FIFO empty: can send next char */
}
Debugging Skills
The Edwards Way to Debug

1. Identify undesired behavior
2. Construct linear model for desired behavior
3. Pick a point along model
4. Form desired behavior hypothesis for point
5. Test
6. Move point toward failure if point working, away otherwise
7. Repeat #4–#6 until bug is found
The Xilinx Tool Chain

**HARDWARE FLOW**

- MicroBlaze IP
- MHS File
- System Generator for MicroBlaze
- Core and IP Netlists VHDL Wrapper
- Xilinx Implementation Tools
  - System.ucf
  - System.bit
  - System.edf
  - Hardware

**SOFTWARE FLOW**

- Library Generator
- MSS File
- Peripheral Drivers
- Compiler mb-gcc
- C Source
- Program.out
- HDL Synthesis Tools
Xilinx *platgen* uses this to piece together the netlist from library components. Excerpt:

```plaintext
PORT VIDOUT_GY = VIDOUT_GY, DIR = OUT, VEC = [9:0]
PORT VIDOUT_BCB = VIDOUT_BCB, DIR = OUT, VEC = [9:0]
PORT FPGA_CLK1 = FPGA_CLK1, DIR = IN
PORT RS232_TD = RS232_TD, DIR=OUT

BEGIN microblaze
  PARAMETER INSTANCE = mymicroblaze
  PARAMETER HW_VER = 2.00.a
  PARAMETER C_USE_BARREL = 1
END

BEGIN opb_uartlite
  PARAMETER INSTANCE = myuart
  PARAMETER C_CLK_FREQ = 50_000_000
  PARAMETER C_BASEADDR = 0xFEFF0100
  PARAMETER C_HIGHADDR = 0xFEFF01FF
END
```
The .mss File

Used by Xilinx *libgen* to link software. Excerpt:

```plaintext
BEGIN PROCESSOR
    PARAMETER HW_INSTANCE = mymicroblaze
    PARAMETER DRIVER_NAME = cpu
    PARAMETER DRIVER_VER = 1.00.a
    PARAMETER EXECUTABLE = hello_world.elf
    PARAMETER COMPILER = mb-gcc
    PARAMETER ARCHIVER = mb-ar
    PARAMETER DEFAULT_INIT = EXECUTABLE
    PARAMETER STDIN = myuart
    PARAMETER STDOUT = myuart
END

BEGIN DRIVER
    PARAMETER HW_INSTANCE = myuart
    PARAMETER DRIVER_NAME = uartlite
    PARAMETER DRIVER_VER = 1.00.b
    PARAMETER LEVEL = 1
END
```
Pin assignments and other global chip information.

net sys_clk period = 18.000;
net pixel_clock period = 36.000;

net VIDOUT_GY<0> loc="p9";
net VIDOUT_GY<1> loc="p10";
net VIDOUT_GY<2> loc="p11";

net VIDOUT_BCB<0> loc="p42";
net VIDOUT_BCB<1> loc="p43";
net VIDOUT_BCB<2> loc="p44";

net FPGA_CLK1 loc="p77";

net RS232_TD loc="p71";
Lab 1

Write and execute a C program that counts in decimal on the two 7-segment displays on the XSB-300E.

We supply

- A hardware configuration consisting of a processor, UART, and
- A simple memory-mapped peripheral that latches and displays a byte controlling each segment of the displays.
- A skeleton project that compiles, downloads, and prints “Hello World” through the serial debugging cable.
Your Job

Write and test C code that

- Counts
- Converts the number into arabic numerals on the display
- Transmits this to the display

*Goal: Learn basics of the tools, low-level C coding, and memory-mapped I/O.*
Debugging Lab 1

- Examine build error messages for hints
- “make clean” sometimes necessary
- Call `print` to send data back to the host
- Run Minicom on `/dev/ttyS0 (9600 8n1)` to observe output