Low-Level C Programming

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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

$+, -$

$\times$

$\div$

sqrt, sin, log, etc.

slower ↓

Simple benchmarks

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

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

Operator	Time	Operator	Time
+ (int)	1	+ (double)	5
* (int)	5	* (double)	5
/ (int)	12	/ (double)	10
« (int)	2	`sqrt`	28
		`sin`	48
		`pow`	275

Simple benchmarks

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

Operator	Time		
+ (int)	1	+ (double)	140
* (int)	1	* (double)	110
/ (int)	7	/ (double)	220
« (int)	1	`sqrt`	500
		`sin`	3300
		`pow`	820

C Arithmetic Trivia

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

Bit Manipulation

C has many bit-manipulation operators.

&	Bit-wise AND
|	Bit-wise OR
^	Bit-wise XOR
~	Negate (one's complement)
»	Right-shift
«	Left-shift

Plus assignment versions of each.

Bit-manipulation basics

```c
a |= 0x4;        /* Set bit 2 */

b &= ˜0x4;       /* Clear bit 2 */

c &= ˜(1 << 3); /* Clear bit 3 */

d ˆ= (1 << 5);  /* Toggle bit 5 */

e >>= 2;         /* Divide e by 4 */
```


Advanced bit manipulation

```c
/* Set b to the rightmost 1 in a */
b = a & (a ˆ (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:

$$\begin{array}{r} 101011 \\ \times\ 1101 \\ \hline 101011 \\ 10101100 \\ +101011000 \\ \hline 1000101111 \end{array} = \texttt{43 + 43 « 2 + 43 « 3} = 559$$

Faking Multiplication

Even more clever if you include subtraction:

$$\begin{array}{r} 101011 \\ \times\ 1110 \\ \hline 1010110 \\ 10101100 \\ +101011000 \\ \hline 1001011010 \end{array} \quad \begin{array}{l} = \texttt{43 « 1 + 43 « 2 + 43 « 3} \\ = \texttt{43 « 4 - 43 « 2} \\ = 602 \end{array}$$

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();
```

```c
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:
```

Microblaze code for switch (1)

```
   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
$L1:
   addk    r3,r3,r3   # Multiply by four
   addk    r3,r3,r3
   lwi     r3,r3,$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
```

Microblaze code for switch (2)

```
   .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
```

Computing Discrete Functions

There are many ways to compute a “random” function of one variable:

```
/* 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;
```


Computing Discrete Functions

```
/* 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 */
```


Function calls

Modern processors, especially RISC, strive to make this cheap. Arguments passed through registers. Still has noticable overhead.

Calling, entering, and returning on the Microblaze:

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


Code for foo()

```
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
```


Strength Reduction

Why multiply when you can add?

```
struct {                  struct {
  int a;                    int a;
  char b;                   char b;
  int c;                    int c;
} foo[10];                } *fp, *fend, foo[10];
int i;                    fend = foo + 10;
for (i=0 ;                for (fp = foo ;
     i<10 ;                    fp != fend ;
     ++i) {                    ++fp) {
  foo[i].a = 77;            fp->a = 77;
  foo[i].b = 88;            fp->b = 88;
  foo[i].c = 99;            fp->c = 99;
}                         }
```

Good optimizing compilers do this automatically.

Unoptimized array code (fragment)

```
$L3:
  lwi      r3,r19,28    # fetch i from stack
  addik    r18,r0,9
  cmp      r18,r18,r3
  blei     r18,$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
```

Optimized pointer code

```
  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
  addik    r5,r0,99
$L12:
  sbi      r6,r3,4       # fp->b = 88
  sw       r7,r0,r3      # fb->a = 77
  swi      r5,r3,8       # fb->c = 99
  addik    r3,r3,12      # ++fp
  rsubk    r18,r4,r3     # fp == fend?
  bnei     r18,$L12
$L14:
  rtsd     r15, 8        # return
  nop
```

How Rapid is Rapid?

How much time does the following loop take?

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

Operation	Cycles per iteration
Memory read	2 or 7
Addition	1
Loop overhead	≈4
Total	6–12

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

$$6 \cdot 1024 \cdot \frac{1}{50\text{MHz}} = 0.12\mu s \text{ or } 12 \cdot 1024 \cdot \frac{1}{50\text{MHz}} = 0.24\mu s$$

Double-checking

GCC generates great code with `-O7`:

```
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.)

Storage Classes in C

```
/* 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

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

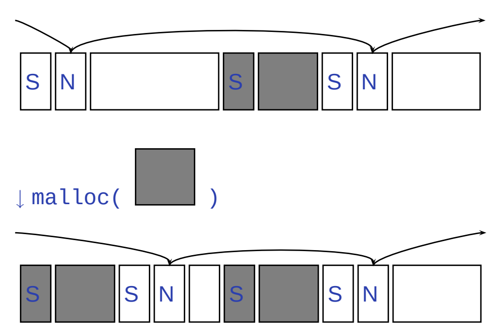
The algorithm for locating a suitable block

Simplest: First-fit

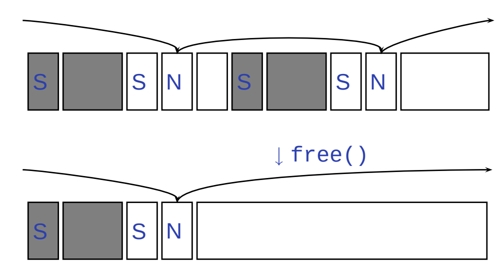
The algorithm for freeing an allocated block

Simplest: Coalesce adjacent free blocks

Dynamic Storage Allocation



Simple Dynamic Storage Allocation



Storage Classes Compared

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

Memory-Mapped I/O

“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

An example

```
#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;
}
```


HW/SW Communication Styles

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”

HW/SW Communication: Interrupts

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.

```
#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;
}
```

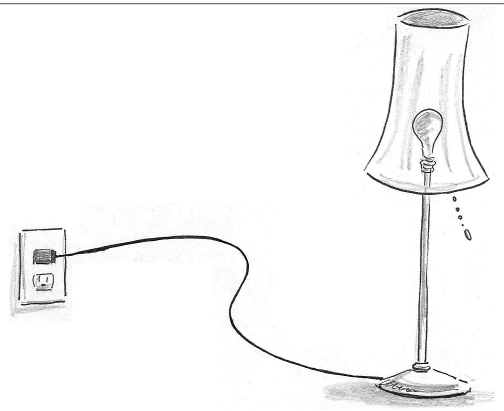
UART interrupts on the Microblaze

```
#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 +
              XIN_MER_OFFSET,
     XIN_INT_MASTER_ENABLE_MASK);
  microblaze_enable_interrupts();
  XUartLite_mEnableIntr(XPAR_MYUART_BASEADDR);
}
```

UART interrupts on the Microblaze

```
#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 */
```

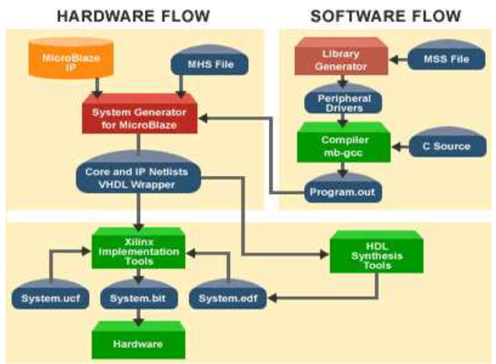
Debugging Skills



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



The .mhs File

Xilinx *platgen* uses this to piece together the netlist from library components. Excerpt:

```
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:

```
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
```


The .ucf file

Pin assigments 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";
```