# 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

```
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 */
```

# Advanced bit manipulation

```
/* 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:

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

# Faking Multiplication

Even more clever if you include subtraction:

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

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

```
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:
```

# 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
        bri     $L14
```

# 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 {
  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;
}
```

```
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.

# 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
```

# 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

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

# 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
```

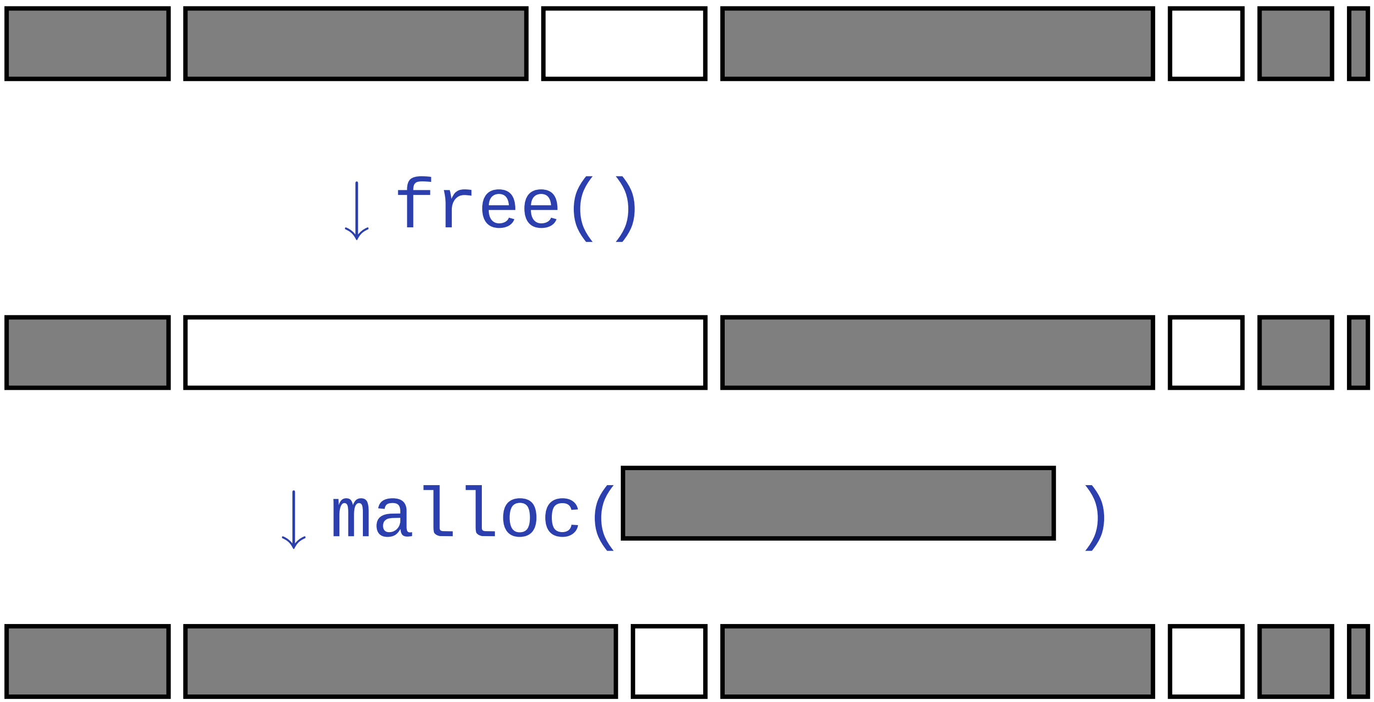
# Features in order of increasing cost

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

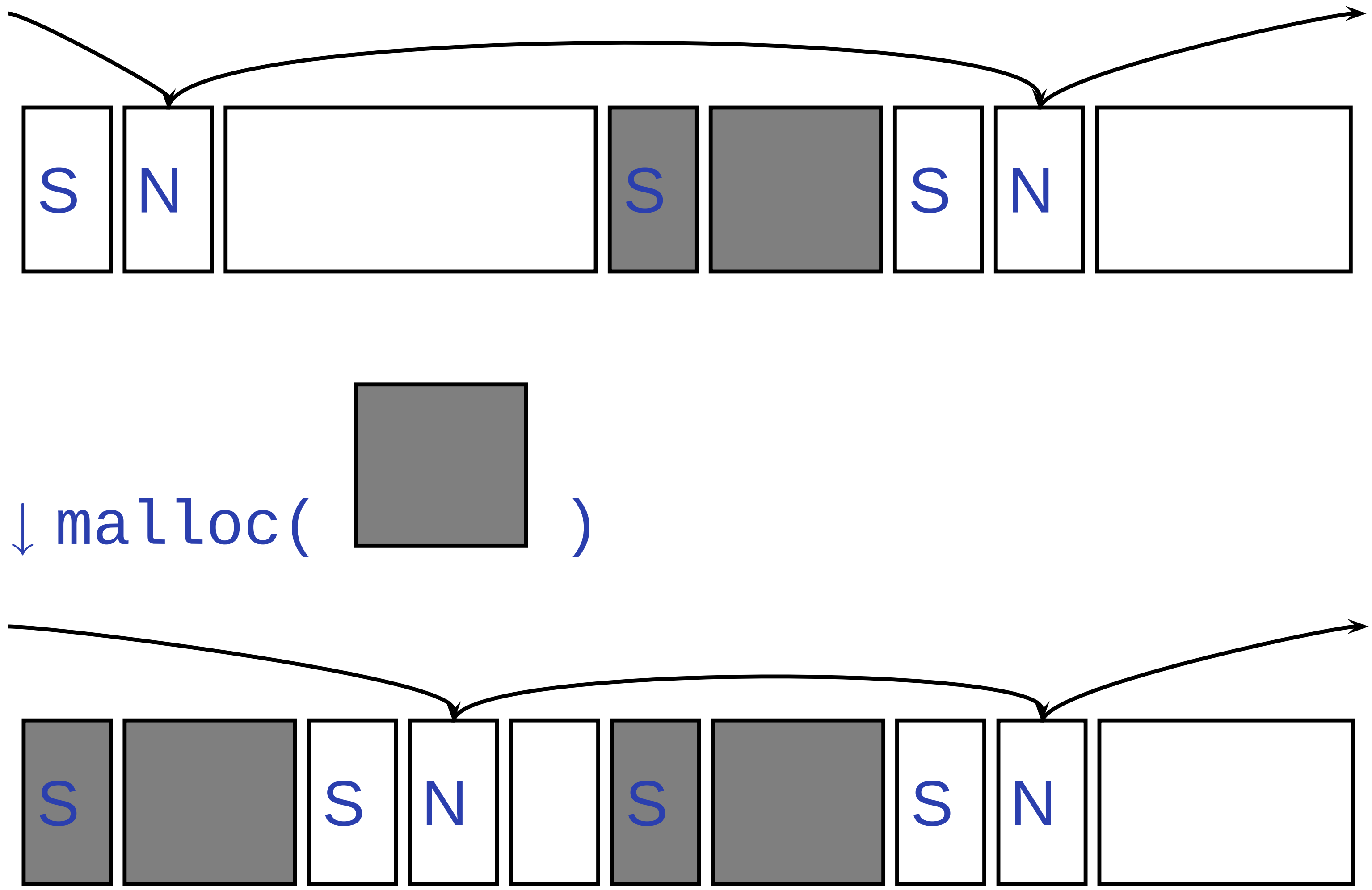
`free()`

- Mark the block as unallocated

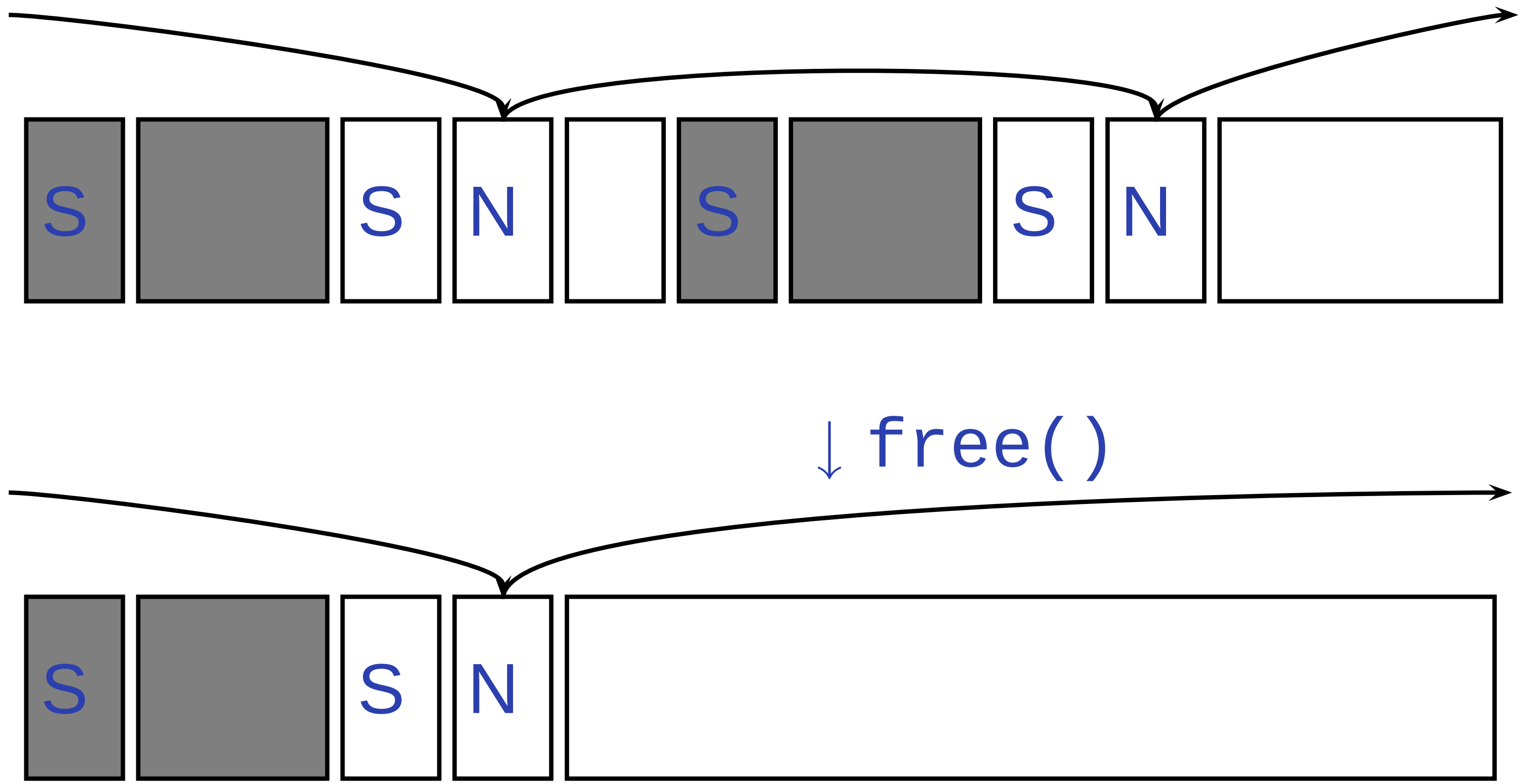
# Simple Dynamic Storage Allocation

- 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;
}
```

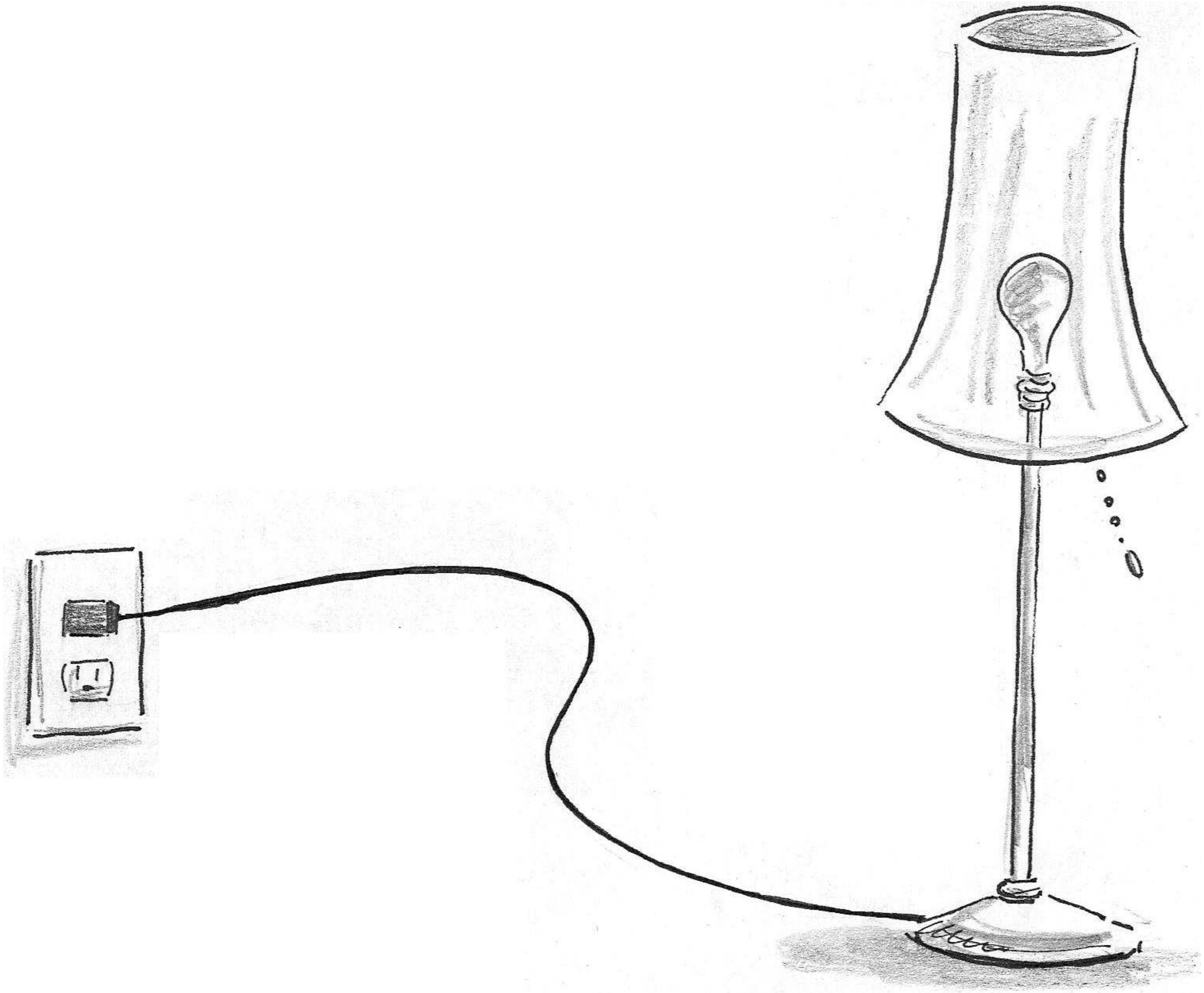
# UART interrupts on the Microblaze

```
#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 interupts 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 */
}
```

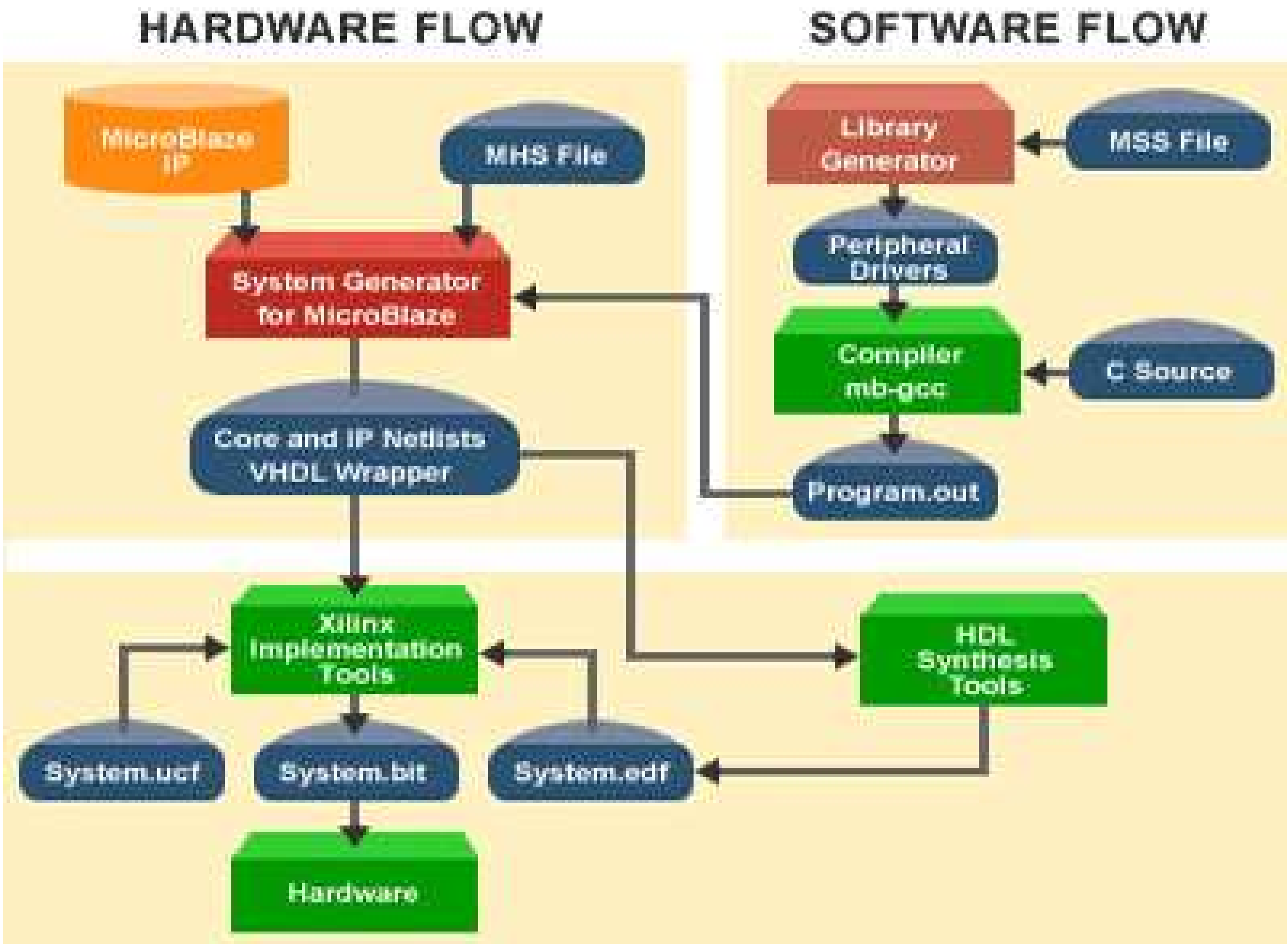
# Debugging Skills



# 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";
```