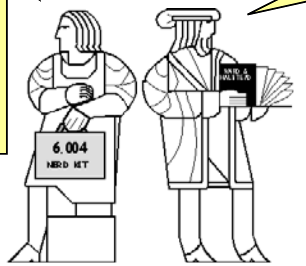
6.004 Computation Structures
Spring 2009

Machine Language, Assemblers, and Compilers

Long, long, time ago, I can still remember
how mnemonics used to make me smile...
And I knew that with just the opcode names
that I could play those BSim games
and maybe hack some macros for a while.
But 6.004 gave me shivers
with every lecture they delivered.
Bad news at the door step,
I couldn't read one more spec.
I can't remember if I tried
to get Factorial optimized,
But something touched my nerdish pride
the day my Beta died.
And I was singing…

When I find my code in tons of trouble,
Friends and colleagues come to me,
Speaking words of wisdom:
"Write in C."



References (on web site):
β Documentation
BSIM reference
Notes on C Language

Quiz 2 *TOMORROW!*

β Machine Language: 32-bit instructions

OPCODE	r_c	r_a	r_b	*unused*

arithmetic: ADD, SUB, MUL, DIV
compare: CMPEQ, CMPLT, CMPLE
boolean: AND, OR, XOR
shift: SHL, SHR, SRA

Ra and Rb are the operands,
Rc is the destination.
R31 reads as 0, unchanged by writes

OPCODE	r_c	r_a	16-bit signed constant

arithmetic: ADDC, SUBC, MULC, DIVC
compare: CMPEQC, CMPLTC, CMPLEC
boolean: ANDC, ORC, XORC
shift: SHLC, SHRC, SRAC
branch: BNE/BT, BEQ/BF (const = word displacement from PC_{NEXT})
jump: JMP (const not used)
memory access: LD, ST (const = byte offset from Reg[ra])

Two's complement 16-bit constant for numbers from –32768 to 32767; sign-extended to 32 bits before use.

How can we improve the programmability of the Beta?

Encoding Binary Instructions

32-bit (4-byte) ADD instruction:

100000	00100	00010	00011	00000000000
OpCode	Rc	Ra	Rb	(unused)

Means, to BETA, Reg[4] = Reg[2] + Reg[3]

But, most of us would prefer to write

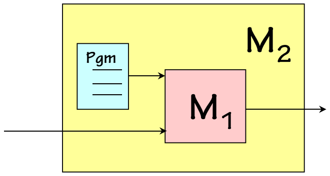
`ADD(R2, R3, R4)` *(ASSEMBLER)*

or, better yet,

`a = b+c;` *(High Level Language)*

Software Approaches: INTERPRETATION, COMPILATION

Interpretation

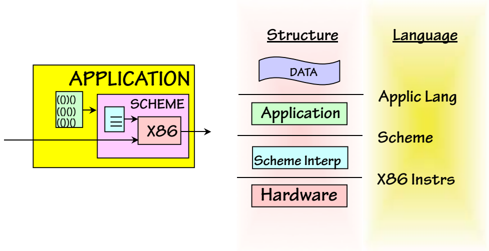


Turing's model of *Interpretation:*

- Start with some hard-to-program *universal* machine, say M_1
- Write a single program for M_1 which mimics the behavior of some easier machine, say M_2
- Result: a "virtual" M_2

"Layers" of interpretation:

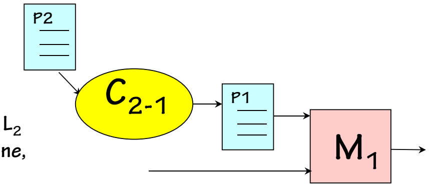
- Often we use several layers of interpretation to achieve desired behavior, eg:
- X86 (Pentium), running
  - Scheme, running
    - Application, interpreting
      - Data.



Compilation

Model of *Compilation:*

- Given some hard-to-program machine, say M_1...
- Find some easier-to-program language L_2 (perhaps for a more complicated machine, M_2); write programs in that language



- Build a translator (compiler) that translates programs from M_2's language to M_1's language. May run on M_1, M_2, or some other machine.

Interpretation & Compilation: two tools for improving programmability ...

- *Both* allow changes in the programming model
- *Both* afford programming applications in platform (e.g., processor) independent languages
- *Both* are widely used in modern computer systems!

Interpretation vs Compilation

There are some characteristic differences between these two powerful tools...

	Interpretation	Compilation
How it treats input "x+2"	computes x+2	generates a program that computes x+2
When it happens	During execution	Before execution
What it complicates/slows	Program Execution	Program Development
Decisions made at	Run Time	Compile Time

Major design choice we'll see repeatedly:
do it at Compile time or at Run time?

Software: Abstraction Strategy

Initial steps: compilation tools

Assembler (UASM): symbolic representation of machine language	Hides: bit-level representations, hex locations, binary values
Compiler (C): symbolic representation of algorithm	Hides: Machine instructions, registers, machine architecture

Subsequent steps: interpretive tools

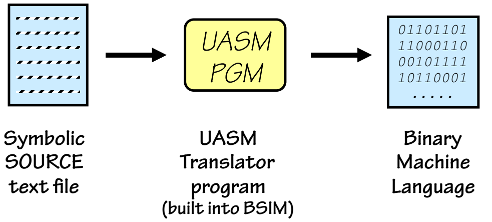
Operating system	Hides: Resource (memory, CPU, I/O) limitiations and details
Apps (e.g., Browser)	Hides: Network; location; local parameters

---

Abstraction step 1:

A Program for Writing Programs

UASM - the 6.004 (Micro) Assembly Language



Symbolic SOURCE text file

UASM Translator program (built into BSIM)

Binary Machine Language

STREAM of Bytes to be loaded into memory

UASM:

1. A Symbolic LANGUAGE for representing strings of bits
2. A PROGRAM ("assembler" = primitive compiler) for translating UASM source to binary.

UASM Source Language

A UASM SOURCE FILE contains, in symbolic text, values of successive bytes to be loaded into memory... e.g. in

`37   -3   255`	decimal (default);
`0b100101`	binary (note the “0b” prefix);
`0x25`	hexadecimal (note the “0x” prefix);

Values can also be expressions; eg, the source file

```
37+0b10-0x10   24-0x1   4*0b110-1   0xF7&0x1F
```

generates 4 bytes of binary output, each with the value **23**!

Symbolic Gestures

We can also define SYMBOLS for use in source programs:

A “bar” denotes the beginning of a comment… The remainder of the line is ignored

```
x = 0x1000          | A variable location
y = 0x1004          | Another variable

| Symbolic names for registers:
R0 = 0
R1 = 1
  ...
R31 = 31
```

Special variable “.” (period) means next byte address to be filled:

```
. = 0x100                | Assemble into 100
   1  2  3  4
five = .                 | Symbol “five” is 0x104
   5  6  7  8
. = .+16                 | Skip 16 bytes
   9 10 11 12
```

Labels (Symbols for Addresses)

LABELS are symbols that represent memory addresses. They can be set with the following special syntax:

`x:` is an abbreviation for “`x = .`”

An Example--

```
---- MAIN MEMORY ----
  1000: 09 04 01 00
  1004: 31 24 19 10
  1008: 79 64 51 40
  100c: E1 C4 A9 90
   1010: 10 … … … …
          3  2  1  0
```

```
. = 0x1000
sqrs:       0 1 4 9
       16 25 36 49
       64 81 100 121
       144 169 196 225
slen:       .-sqrs
```

Mighty Macroinstructions

Macros are parameterized abbreviations, or shorthand

```
| Macro to generate 4 consecutive bytes:
.macro consec(n)  n  n+1  n+2  n+3

| Invocation of above macro:
consec(37)
```

Has same effect as:

```
37    38    39    40
```

Here are macros for breaking multi-byte data types into byte-sized chunks

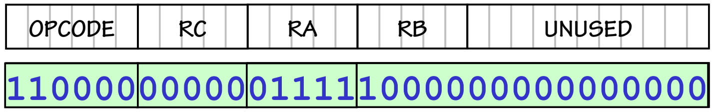
```
| Assemble into bytes, little-endian (least-sig byte 1st)
.macro WORD(x) x%256 (x/256)%256
.macro LONG(x) WORD(x) WORD(x >> 16)

. = 0x100
  LONG(0xdeadbeef)
```

Boy, that's hard to read. Maybe, those big-endian types do have a point.

Has same effect as:

```
       0xef  0xbe  0xad  0xde
Mem: 0x100 0x101 0x102 0x103
```

Assembly of Instructions



```
| Assemble Beta op instructions
.macro betaop(OP,RA,RB,RC) {
    .align 4
    LONG((OP<<26)+((RC%32)<<21)+((RA%32)<<16)+((RB%32)<<11))
}

| Assemble Beta opc instructions
.macro betaopc(OP,RA,CC,RC) {
    .align 4
    LONG((OP<<26)+((RC%32)<<21)+((RA%32)<<16)+(CC % 0x10000))
}

| Assemble Beta branch instructions
.macro betabr(OP,RA,RC,LABEL)     betaopc(OP,RA,((LABEL-(.+4))>>2),RC)
```

".align 4" ensures instructions will begin on word boundary (i.e., address = 0 mod 4)

Arrgh!

```
For Example:

        ADDC(R15, -32768, R0) --> betaopc(0x30,15,-32768,0)
```

Finally, Beta Instructions

```
| BETA Instructions:
.macro ADD(RA,RB,RC)    betaop(0x20,RA,RB,RC)
.macro ADDC(RA,C,RC)    betaopc(0x30,RA,C,RC)
.macro AND(RA,RB,RC)            betaop(0x28,RA,RB,RC)
.macro ANDC(RA,C,RC)            betaopc(0x38,RA,C,RC)
.macro MUL(RA,RB,RC)    betaop(0x22,RA,RB,RC)
.macro MULC(RA,C,RC)    betaopc(0x32,RA,C,RC)
    :
    .
.macro LD(RA,CC,RC)     betaopc(0x18,RA,CC,RC)
.macro LD(CC,RC)        betaopc(0x18,R31,CC,RC)
.macro ST(RC,CC,RA)     betaopc(0x19,RA,CC,RC)
.macro ST(RC,CC)        betaopc(0x19,R31,CC,RC)
    :
    .
.macro BEQ(RA,LABEL,RC) betabr(0x1D,RA,RC,LABEL)
.macro BEQ(RA,LABEL)    betabr(0x1D,RA,r31,LABEL)
.macro BNE(RA,LABEL,RC) betabr(0x1E,RA,RC,LABEL)
.macro BNE(RA,LABEL)    betabr(0x1E,RA,r31,LABEL)
```

Convenience macros so we don't have to specify R31…

(from beta.uasm)

Example Assembly

`ADDC(R3,1234,R17)`

↓ expand ADDC macro with RA=R3, C=1234, RC=R17

`betaopc(0x30,R3,1234,R17)`

↓ expand betaopc macro with OP=0x30, RA=R3, CC=1234, RC=R17

```
.align 4
LONG((0x30<<26)+((R17%32)<<21)+((R3%32)<<16)+(1234 % 0x10000))
```

↓ expand LONG macro with X=0xC22304D2

`WORD(0xC22304D2)   WORD(0xC22304D2 >> 16)`

↓ expand first WORD macro with X=0xC22304D2

`0xC22304D2%256   (0xC22304D2/256)%256   WORD(0xC223)`

↓ evaluate expressions, expand second WORD macro with X=0xC223

`0xD2   0x04   0xC223%256   (0xC223/256)%256`

↓ evaluate expressions

`0xD2   0x04   0x23   0xC2`

Don't have it? Fake it!

Convenience macros can be used to extend our assembly language:

```
.macro MOVE(RA,RC)          ADD(RA,R31,RC)     | Reg[RC] <- Reg[RA]
.macro CMOVE(CC,RC)         ADDC(R31,C,RC)     | Reg[RC] <- C

.macro COM(RA,RC)                   XORC(RA,-1,RC)    | Reg[RC] <-
   ~Reg[RA]
.macro NEG(RB,RC)                   SUB(R31,RB,RC)    | Reg[RC] <-
   -Reg[RB]
.macro NOP()                ADD(R31,R31,R31) | do nothing

.macro BR(LABEL)            BEQ(R31,LABEL)     | always branch
.macro BR(LABEL,RC)         BEQ(R31,LABEL,RC)         | always
   branch
.macro CALL(LABEL)          BEQ(R31,LABEL,LP)         | call
   subroutine
.macro BF(RA,LABEL,RC)      BEQ(RA,LABEL,RC) | 0 is false
.macro BF(RA,LABEL)         BEQ(RA,LABEL)
.macro BT(RA,LABEL,RC)      BNE(RA,LABEL,RC) | 1 is true
.macro BT(RA,LABEL)         BNE(RA,LABEL)

| Multi-instruction sequences
.macro PUSH(RA)             ADDC(SP,4,SP)   ST(RA,-4,SP)
.macro POP(RA)              LD(SP,-4,RA)    ADDC(SP,-4,SP)
```

(from beta.uasm)

Abstraction step 2:

High-level Languages

Most algorithms are naturally expressed at a high level. Consider the following algorithm:

```
struct Employee
 { char *Name;    /* Employee's name. */
   long Salary; /* Employee's salary. */
   long Points;}/* Brownie points. */

/* Annual raise program. */
Raise(struct Employee P[100])
 { int i = 0;
   while (i < 100)
    { struct Employee *e = &P[i];
      e->Salary =
           e->Salary + 100 + e->Points;
      e->Points = 0;  /* Start over! */
      i = i+1;
    }
 }
```

Reference: C handout (6.004 web site)

We've used (and will continue to use throughout 6.004) C, a "mature" and common systems programming lanugage. Modern popular alternatives include C++, Java, Python, and many others.

Why use these, not assembler?

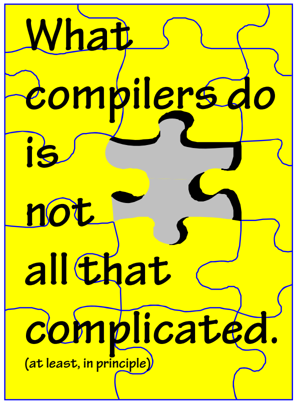
- readable
- concise
- unambiguous
- portable
  (algorithms frequently outlast their HW platforms)
- Reliable (type checking, etc)

How Compilers Work

Contemporary compilers go far beyond the macro-expansion technology of UASM. They

- Perform sophisticated analyses of the source code
- Invoke arbitrary algorithms to generate efficient object code for the target machine
- Apply "optimizations" at both source and object-code levels to improve run-time efficiency.

Compilation to ***unoptimized*** code is pretty straightforward... following is a brief glimpse.



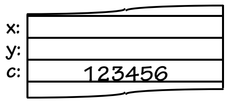
Compiling Expressions

C code:

```
int x, y;
y = (x-3)*(y+123456)
```

Beta assembly code:

```
x:    LONG(0)
y:    LONG(0)
c:    LONG(123456)
...
   LD(x, r1)
   SUBC(r1,3,r1)
   LD(y, r2)
   LD(C, r3)
   ADD(r2,r3,r2)
   MUL(r2,r1,r1)
   ST(r1,y)
```



- VARIABLES are assigned memory locations and accessed via LD or ST
- OPERATORS translate to ALU instructions
- SMALL CONSTANTS translate to "literal-mode" ALU instructions
- LARGE CONSTANTS translate to initialized variables

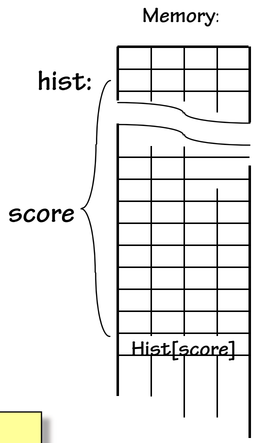
Data Structures: Arrays

The C source code

```
int Hist[100];
...
Hist[score] += 1;
```

might translate to:

```
hist:   .=.+4*100 | Leave room for 100 ints
...
<score in r1>
MULC(r1,4,r2)     | index -> byte offset
LD(r2,hist,r0)    | hist[score]
ADDC(r0,1,r0)     | increment
ST(r0,hist,r2)    | hist[score]
```



Address:
CONSTANT base address +
VARIABLE offset computed from index

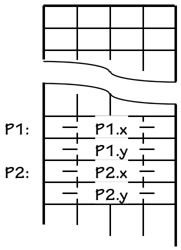
Data Structures: Structs

```
struct Point
  { int x, y;
  } P1, P2, *p;
...
P1.x = 157;
...
p = &P1;
p->y = 157;
```

might translate to:

```
P1: .=.+8
P2: .=.+8
x=0                | Offset for x component
y=4                | Offset for y component
...
CMOVE(157,r0)          | r0 <- 157
ST(r0,P1+x)            | P1.x = 157
...
<p in r3>
ST(r0,y,r3)            | p->y = 157;
```

Memory:



Address:
VARIABLE base address +
CONSTANT component offset

Conditionals

C code:

```
if (expr)
  {
     STUFF
  }
```

Beta assembly:

```
    (compile expr into rx)
    BF(rx, Lendif)
    (compile STUFF)
Lendif:
```

C code:

```
if (expr)
  {
     STUFF1
  }
else
  {
     STUFF2
  }
```

Beta assembly:

```
    (compile expr into rx)
    BF(rx, Lelse)
    (compile STUFF1)
    BR(Lendif)
Lelse:
    (compile STUFF2)
Lendif:
```

There are little tricks that come into play when compiling conditional code blocks. For instance, the statement:

```
if (y > 32)
  {
     x = x + 1;
  }
```

there's no >32 instruction!

compiles to:

```
 LD(y,R1)
  CMPLEC(R1,32,R1)
  BT(R1,Lendif)
  ADDC(R2,1,R2)
Lendif:
```

Loops

C code:

```
while (expr)
 {
    STUFF
 }
```

Beta assembly:

```
Lwhile:
    (compile expr into rx)
    BF(rx,Lendwhile)
    (compile STUFF)
    BR(Lwhile)
Lendwhile:
```

Alternate Beta assembly:

```
   BR(Ltest)
Lwhile:
   (compile STUFF)
Ltest:
    (compile expr into rx)
    BT(rx,Lwhile)
Lendwhile:
```

Move the test to the end of the loop and branch there the first time thru… saves a branch

Compilers spend a lot of time optimizing in and around loops.
- moving all possible computations outside of loops
- "*unrolling*" loops to reduce branching overhead
- simplifying expressions that depend on "loop variables"

Our Favorite Program

```
int n = 20, r;

r = 1;

while (n > 0)
{

   r = r*n;

   n = n-1;

}
```

```
n: LONG(20)
r: LONG(0)
start:
    ADDC(r31, 1, r0)
    ST(r0, r)
loop:
    LD(n, r1)
    CMPLT(r31, r1, r2)
    BF(r2, done)
    LD(r, r3)
    LD(n,r1)
    MUL(r1, r3, r3)
    ST(r3, r)
    LD(n,r1)
    SUBC(r1, 1, r1)
    ST(r1, n)
    BR(loop)
done:
```

Cleverness:
  None…
  straightforward
  compilation

(11 instructions in loop...)

Optimizations are what make compilers ~~complicated~~ interesting!

Optimizations

int n = 20, r;

r = 1;

while (n > 0)
{
 r = r*n;
 n = n-1;
}

```
n: LONG(20)
r: LONG(0)

start:
   ADDC(r31, 1, r0)
   ST(r0, r)
   LD(n,r1)     | keep n in r1
   LD(r,r3)     | keep r in r3

loop:
   CMPLT(r31, r1, r2)
   BF(r2, done)
   MUL(r1, r3, r3)
   SUBC(r1, 1, r1)
   BR(loop)

done:
   ST(r1,n)     | save final n
   ST(r3,r)     | save final r
```

Cleverness:
We move LDs/STs out of loop!

(Still, 5 instructions in loop...)

Really Optimizing...

int n = 20, r;

r = 1;

while (n > 0)
{ r = r*n;
 n = n-1;
}

```
n: LONG(20)
r: LONG(0)

start:
   LD(n,r1)            | keep n in r1
   ADDC(r31,1,r3)      | keep r in r3
   BEQ(r1, done)       | why?
loop:
   MUL(r1, r3, r3)
   SUBC(r1, 1, r1)
   BNE(r1,loop)
done:
   ST(r1,n)             | save final n
   ST(r3,r)             | save final r
```

Cleverness:
We avoid overhead of conditional!

(Now 3 instructions in loop...)

UNFORTUNATELY,
20! = 2,432,902,008,176,640,000 > 2^{61} *(overflows!)*
but **12!** = 479,001,600 = **0x1c8cfc00**

Coming Attractions:

Procedures & Stacks