CPSC 213

Introduction to Computer Systems

Unit 1b

Scalars and Arrays

Reading

- Companion
  - 2.2.3, 2.3, 2.4.1-2.4.3, 2.6
- Textbook
  - *Array Allocation and Access*
  - 1ed: 3.8
  - 2ed: 3.8

Design Plan

Examine Java and C Piece by Piece

- Reading writing and arithmetic on variables
  - static base types (e.g., int, char)
  - static and dynamic arrays of base types
  - dynamically allocated objects/structs and object references
  - object instance variables
  - procedure locals and arguments
- Control flow
  - static intra-procedure control flow (e.g., if, for, while)
  - static procedure calls
  - dynamic control flow

Java and C: Many Syntax Similarities

- similar syntax for many low-level operations

- declaration, assignment
  - int a = 4;
- control flow (often)
  - if (a == 4) ... else ...
  - for (int i = 0; i < 10; i++) {...}
  - while (i < 10) {...}
- casting

  int a;
  long b;
  a = (int) b;

Java and C: Many Differences

- some syntax differences, many deeper differences
  - C is not (intrinsically) object oriented
  - ancestor of both Java and C++
- more details as we go!

Java Hello World...

```
import java.io.*;
public class HelloWorld {
  public static void main (String[] args) {
    System.out.println("Hello world");
 }
}
```

C Hello World...

```
#include <stdio.h>
main() {
    printf("Hello world\n");
}
```

Design Tasks

- Design Instructions for SM213 ISA
  - design instructions necessary to implement the languages
  - keep hardware simple/fast by adding as few/simple instructions possible
- Develop Compilation Strategy
  - determine how compiler will compile each language feature it sees
  - which instructions will it use?
  - in what order?
  - what can compiler compute statically?
- Consider Static and Dynamic Phases of Computation
  - the static phase of computation (compilation) happens just once
  - the dynamic phase (running the program) happens many times
  - thus anything the compiler computes, saves execution time later

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The Simple Machine (SM213) ISA

- Architecture

Register File	8, 32-bit general purpose registers
CPU	one cycle per instruction (fetch + execute)
Main Memory	byte addressed, Big Endian integers

- Instruction Format
  - 2 or 6 byte instructions (each character is a hex digit)
    - **x-sd**, **xsd-**, **xxsd**, **xsvv, xxvs**, or **xs-- vvvvvvvv**
  - where
    - **x** or **xx** is *opcode* (unique identifier for this instruction)
    - **-** means unused
    - **s** and **d** are operands (registers), sometimes left blank with **-**
    - **vv** and **vvvvvvvv** are immediate / constant values

Machine and Assembly Syntax

Machine code

- [addr:] x-01 [vvvvvvvv]
  - addr: sets starting address for subsequent instructions
  - x-01 hex value of instruction with opcode x and operands 0 and 1
  - vvvvvvvv hex value of optional extended value part instruction

Assembly code

- ([label:] [instruction | directive] [# comment] |)*
  - directive :: (.pos number) | (.long number)
  - instruction :: opcode operand+
  - operand :: $literal | reg | offset (reg) | (reg,reg,4)
  - reg :: r 0..7
  - literal :: number
  - offset :: number
  - number :: decimal | 0x hex

Register Transfer Language (RTL)

Goal

- a simple, convenient pseudo language to describe instruction semantics
- easy to read and write, directly translated to machine steps

Syntax

- each line is of the form LHS ← RHS
- LHS is memory or register specification
- RHS is constant, memory, or arithmetic expression on two registers

Register and Memory are treated as arrays

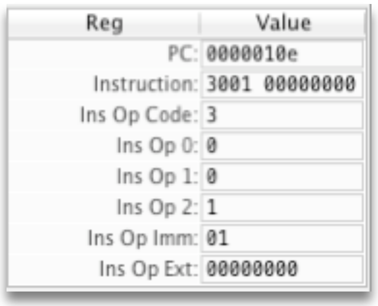
- m[a] is memory location at address a
- r[i] is register number i

For example

- r[0] ← 10
- r[1] ← m[r[0]]
- r[2] ← r[0] + r[1]

Implementing the ISA

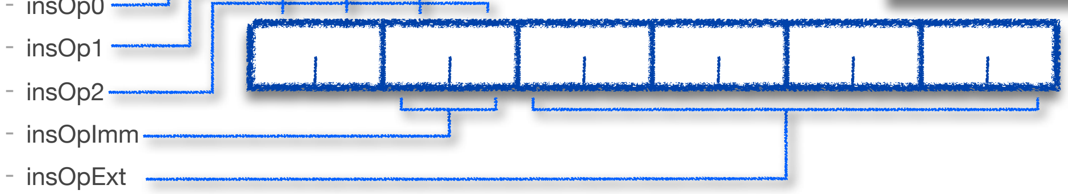
The CPU Implementation



Reg	Value
PC:	0000010e
Instruction:	3001 00000000
Ins Op Code:	3
Ins Op 0:	0
Ins Op 1:	0
Ins Op 2:	1
Ins Op Imm:	01
Ins Op Ext:	00000000

Internal state

- pc address of ***next*** instruction to fetch
- instruction the value of the current instruction



  - insOpCode
  - insOp0
  - insOp1
  - insOp2
  - insOpImm
  - insOpExt

Operation

- fetch
  - read instruction at pc from memory, determine its size and read all of it
  - separate the components of the instruction into sub-registers
  - set pc to store address of next instruction, sequentially
- execute
  - use insOpCode to select operation to perform
  - read internal state, memory, and/or register file
  - update memory, register file and/or pc

Static Variables of Built-In Types

Static Variables, Built-In Types (S1-global-static)

- Java
  - static data members are allocated to a class, not an object
  - they can store built-in scalar types or references to arrays or objects (references later)

```
public class Foo {
  static int   a;
  static int[] b;   // array is not static, so skip for now

  public void foo () {
    a = 0;
  }}
```

- C
  - global variables and any other variable declared static
  - they can be static scalars, arrays or structs or pointers (pointers later)

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

Static Variable Allocation

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

```
int a;
int b[10];
```

- Allocation is
  - assigning a memory location to store variable's value
  - assigning the variable an address (its name for reading and writing)
- Key observation
  - global/static variables can exist before program starts and live until after it finishes
- Static vs dynamic computation
  - compiler allocates variables, giving them a constant address
  - no dynamic computation required to allocate the variables, they just exist

---

Static Variable Allocation

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

```
int a;
int b[10];
```

Static Memory Layout

```
0x1000: value of a
0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]
```

- Allocation is
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Static Variable Access (scalars)

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

a = 0;

b[a] = a;

Static Memory Layout

0x1000: value of a
0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]

- Key Observation
  - address of **a**, **b[0]**, **b[1]**, **b[2]**, ... are constants known to the compiler
- Use RTL to specify instructions needed for **a = 0**

Static Variable Access (scalars)

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

a = 0;

b[a] = a;

Static Memory Layout

0x1000: value of a
0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]

- Key Observation
  - address of **a**, **b[0]**, **b[1]**, **b[2]**, ... are constants known to the compiler
- Use RTL to specify instructions needed for **a = 0**

Generalizing
* What if it's a = a + 2? or a = b? or a = foo ()?
* What about reading the value of a?

Question (scalars)

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

a = 0;

b[a] = a;

Static Memory Layout

0x1000: value of a
0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]

- When is space for **a** allocated (when is its address determined)?
  - [A] The program locates available space for **a** when program starts
  - [B] The compiler assigns the address when it compiles the program
  - [C] The compiler calls the memory to allocate **a** when it compiles the program
  - [D] The compiler generates code to allocate **a** before the program starts running
  - [E] The program locates available space for **a** when the program starts running
  - [F] The program locates available space for **a** just before calling **foo()**

Static Variable Access (static arrays)

```
int a;
int b[10];

void foo () {
  a    = 0;
  b[a] = a;
}
```

a = 0;

b[a] = a;

Static Memory Layout

0x1000: value of a
0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]

- Key Observation
  - compiler does not know address of **b[a]**
    - unless it can knows the value of a statically, which it could here by looking at a=0, but not in general
- Array access is computed from base and index
  - address of element is *base* plus *offset*; *offset* is *index* times element size
  - the base address (0x2000) and element size (4) are static, the index is dynamic
- Use RTL to specify instructions for **b[a] = a**, not knowing **a**?

Designing ISA for Static Variables

- Requirements for scalars `a = 0;`
  - load constant into register
    - r[x] ← v
  - store value in register into memory at constant address
    - m[0x1000] ← r[x]
  - load value in memory at constant address into a register
    - r[x] ← m[0x1000]
- Additional requirements for arrays `b[a] = a;`
  - store value in register into memory at address in register*4 plus constant
    - m[0x2000+r[x]*4] ← r[y]
  - load value in memory at address in register*4 plus constant into register
    - r[y] ← m[0x2000+r[x]*4]
- Generalizing and simplifying we get
  - r[x] ← constant
  - m[r[x]] ← r[y] and r[y] ← m[r[x]]
  - m[r[x] + r[y]*4] ← r[z] and r[z] ← m[r[x] + r[y]*4]

- The compiler's semantic translation
  - it uses these instructions to compile the program snippet

```
int a;
int b[10];

void foo () {
  a = 0;
  b[a] = a;
}
```

```
r[0]             ← 0
r[1]             ← 0x1000
m[r[1]]          ← r[0]

r[2]             ← m[r[1]]
r[3]             ← 0x2000
m[r[3]+r[2]*4] ← r[2]
```

- ISA Specification for these 5 instructions

Name	Semantics	Assembly	Machine
load immediate	r[d] ← v	ld $v, rd	0d-- vvvvvvvv
load base+offset	r[d] ← m[r[s]]	ld ?(rs), rd	1?sd
load indexed	r[d] ← m[r[s]+4*r[i]]	ld (rs,ri,4), rd	2sid
store base+offset	m[r[d]] ← r[s]	st rs, ?(rd)	3s?d
store indexed	m[r[d]+4*r[i]] ← r[s]	st rs, (rd,ri,4)	4sdi

- The compiler's assembly translation

```
int a;
int b[10];

void foo () {
  a = 0;
  b[a] = a;
}
```

```
r[0]             ← 0
r[1]             ← 0x1000
m[r[1]]          ← r[0]

r[2]             ← m[r[1]]
r[3]             ← 0x2000
m[r[3]+r[2]*4] ← r[2]
```

```
int a;
int b[10];

void foo () {
  a = 0;
  b[a] = a;
}
```

```
ld $0, r0
ld $0x1000, r1
st r0, (r1)

ld (r1), r2
ld $0x2000, r3
st r2, (r3,r2,4)
```

- If a human wrote this assembly
  - list static allocations, use labels for addresses, add comments

```
int a;
int b[10];

void foo () {
  a = 0;
  b[a] = a;
}
```

```
ld $0, r0         # r0 = 0
ld $a_data, r1    # r1 = address of a
st r0, (r1)       # a = 0

ld (r1), r2       # r2 = a
ld $b_data, r3    # r3 = address of b
st r2, (r3,r2,4) # b[a] = a

.pos 0x1000
a_data:
.long 0           # the variable a

.pos 0x2000
b_data:
.long 0           # the variable b[0]
.long 0           # the variable b[1]
...
.long 0           # the variable b[9]
```

Addressing Modes

- In these instructions

Name	Semantics	Assembly	Machine
load immediate	r[d] ← v	ld $v, rd	0d-- vvvvvvvv
load base+offset	r[d] ← m[r[s]]	ld ?(rs), rd	1?sd
load indexed	r[d] ← m[r[s]+4*r[i]]	ld (rs,ri,4), rd	2sid
store base+offset	m[r[d]] ← r[s]	st rs, ?(rd)	3s?d
store indexed	m[r[d]+4*r[i]] ← r[s]	st rs, (rd,ri,4)	4sdi

- We have specified 4 *addressing modes* for operands

immediate	constant value stored in instruction
register	operand is register number, register stores value
base+offset	operand in register number register stores memory address of value
indexed	two register-number operands store base memory address and index of value

---

ALU: Arithmetic, Shifting, NOP, Halt

- Arithmetic

Name	Semantics	Assembly	Machine
register move	r[d] ← r[s]	mov rs, rd	60sd
add	r[d] ← r[d] + r[s]	add rs, rd	61sd
and	r[d] ← r[d] & r[s]	and rs, rd	62sd
inc	r[d] ← r[d] + 1	inc rd	63-d
inc address	r[d] ← r[d] + 4	inca rd	64-d
dec	r[d] ← r[d] – 1	dec rd	65-d
dec address	r[d] ← r[d] – 4	deca rd	66-d
not	r[d] ← ~ r[d]	not rd	67-d

- Shifting NOP and Halt

Name	Semantics	Assembly	Machine
shift left	r[d] ← r[d] << S = s	shl rd, s	7dSS
shift right	r[d] ← r[d] >> S = -s	shr rd, s	
halt	*halt machine*	halt	f0--
nop	*do nothing*	nop	ff--

Global Dynamic Array

Global Dynamic Array

- Java
  - array variable stores reference to array allocated dynamically with **new** statement

```
public class Foo {
  static int a;
  static int b[] = new int[10];

  void foo () {
    b[a]=a;
  }}
```

- C
  - array variables can store static arrays or pointers to arrays allocated dynamically with call to **malloc** library procedure

```
int  a;
int* b;

void foo () {
  b = (int*) malloc (10*sizeof(int));
  b[a] = a;
}
```

Global Dynamic Array

- Java
  - array variable stores reference to array allocated dynamically with **new** statement

```
public class Foo {
  static int a;
  static int b[] = new int[10];

  void foo () {
    b[a]=a;
}}
```

- C
  - array variables can store static arrays or
    pointers to arrays allocated dynamically with call to **malloc** library procedure

```
int  a;
int* b;

void foo () {
  b = (int*) malloc (10*sizeof(int));
  b[a] = a;
}
```

malloc does not assign a type

\# of bytes to allocate

How C Arrays are Different from Java

- Terminology
  - use the term ***pointer*** instead of ***reference***; they mean the same thing
  - stay tuned for more on pointers later
- Declaration
  - the type is a pointer to the type of its elements, indicated with a *
- Allocation
  - malloc allocates a block of bytes; no type; no constructor
- Type Safety
  - any pointer can be type cast to any pointer type
- Bounds checking
  - C performs no array bounds checking
  - out-of-bounds access manipulates memory that is not part of array
  - this is the major source of virus vulnerabilities in the world today

How C Arrays are Different from Java

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  - out-of-bounds access manipulates memory that is not part of array
  - this is the major source of virus vulnerabilities in the world today

Question: Can array bounds checking be perform statically?
 * what does this say about a tradeoff that Java and C take differently?

Static vs Dynamic Arrays

- Declared and allocated differently, but accessed the same

```
int a;
int b[10];

void foo () {
  b[a] = a;
}
```

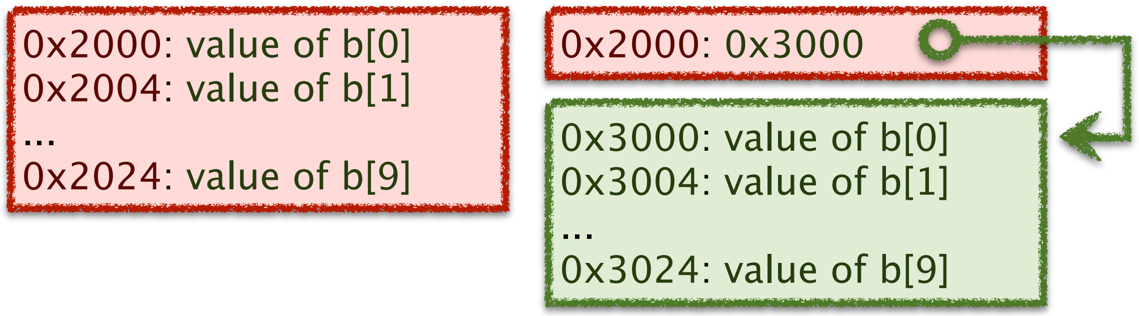
```
int  a;
int* b;

void foo () {
  b = (int*) malloc (10*sizeof(int));
  b[a] = a;
}
```

- Static allocation
  - for static arrays, the compiler allocates the array
  - for dynamic arrays, the compiler allocates a pointer

```
0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]
```

```
0x2000: value of b
```

- Then when the program runs
  - the dynamic array is allocated by a call to malloc, say at address 0x3000
  - the value of variable b is set to the memory address of this array



0x2000: value of b[0]
0x2004: value of b[1]
...
0x2024: value of b[9]

0x2000: 0x3000

0x3000: value of b[0]
0x3004: value of b[1]
...
0x3024: value of b[9]

- Generating code to access the array
  - for the dynamic array, the compiler generates an additional load for b

```
r[0]          ← 0x1000
r[1]          ← m[r[0]]
r[2]          ← 0x2000
m[r[2]+r[1]*4] ← r[1]
```

```
r[0]          ← 0x1000
r[1]          ← m[r[0]]
r[2]          ← 0x2000
r[3]          ← m[r[2]]
m[r[3]+r[2]*4] ← r[2]
```

load a

load b
b[a]=a

- In assembly language

Static Array

```
ld $a_data, r0   # r0 = address of a
ld (r0), r1      # r1 = a
ld $b_data, r2   # r2 = address of b
st r1, (r2,r1,4) # b[a] = a

.pos 0x1000
a_data:
.long 0          # the variable a

.pos 0x2000
b_data:
.long 0          # the variable b[0]
.long 0          # the variable b[1]
...
.long 0          # the variable b[9]
```

Dynamic Array

```
ld $a_data, r0   # r0 = address of a
ld (r0), r1      # r1 = a
ld $b_data, r2   # r2 = address of b
ld (r2), r3      # r3 = b
st r1, (r3,r1,4) # b[a] = a

.pos 0x1000
a_data:
.long 0          # the variable a

.pos 0x2000
b_data:
.long 0          # the b
```

- Comparing static and dynamic arrays
  - what is the benefit of static arrays?
  - what is the benefit of dynamic arrays?

Summary: Scalar and Array Variables

- Static variables
  - the compiler knows the address (memory location) of variable
- Static scalars and arrays
  - the compiler knows the address of the scalar value or array
- Dynamic arrays
  - the compiler does not know the address the array
- What C does that Java doesn’t
  - static arrays
  - more later... stay tuned!
- What Java does that C doesn’t
  - typesafe dynamic allocation
  - automatic array-bounds checking