Poll: Who is responsible for erasing a whiteboard in a public space?

a) The person who is done using it
b) The person who is about to use it

EECS 370 - Lecture 6

Function Calls

Instruction Set Architecture (ISA) Design Lectures

- Lecture 2: ISA - storage types, binary and addressing modes
- Lecture 3 : LC2K
- Lecture 4 : ARM
- Lecture 5 : Converting C to assembly – basic blocks
- **Lecture 6 : Converting C to assembly – functions**
- Lecture 7 : Translation software; libraries, memory layout

Agenda

- **Using branches more generally**
- Function calls and the call stack
- Assigning variables to memory locations
- Saving registers
- Caller/callee example

Branching far away

- Underlying philosophy of ISA design: **make the common case fast**
- Most branches target nearby instructions
  - Displacement of 19 bits is usually enough
- BUT what if we need to branch really far away (more than 2^{19} words)?

```
CBZ     X15, FarLabel
```

- The assembler is smart enough to replace that with

```
        CBNZ    X15, L1
        B       FarLabel
L1:     .......
```

- The simple branch instruction (B) has a 26 bit offset which spans about 64 million instructions!
- In LC2K, we can do a similar thing by using JALR instead of BEQ

Unconditional Branching Instructions

Unconditional branch	branch	B	2500	go to PC + 10000	Branch to target address; PC-relative
	branch to register	BR	X30	go to X30	For switch, procedure return
	branch with link	BL	2500	X30 = PC + 4; PC = PC + 10000	For procedure call PC-relative

- There are three types of unconditional branches in the LEGv8 ISA.
  - The first **(B)** is the PC relative branch with the 26 bit offset from the last slide.
  - The second **(BR)** jumps to the address contained in a register (X30 above)
  - The third **(BL)** is like our PC relative branch but it does something else.
    - It sets X30 (always) to be the current PC+4 before it branches.
- Why is BL storing PC+4 into a register? (return to current pos after branching)

Branch with Link (BL)

- Branch with Link is the branch instruction used to call functions
  - Functions need to know where they were called from so they can return.
    - In particular they will need to return to right after the function call
    - Can use "BR X30"
- Say that we execute the instruction BL #200 when at PC 1000.
  - What address will be branched to?
  - What value is stored in X30?
  - How is that value in X30 useful?

Poll

Agenda

- Using branches more generally
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Converting function calls to assembly code

C: factorial(5);

- Need to pass parameters to the called function—factorial
- Need to save return address of caller so we can get back
- Need to save register values (why?)
- Need to jump to factorial

Execute instructions for factorial()
Jump to return address

- Need to get return value (if used)
- Restore register values

Task 1: Passing parameters

- Where should you put all of the parameters?
  - Registers?
    - Fast access but few in number and wrong size for some objects
  - Memory?
    - Good general solution but slow
- ARMv8 solution—and the usual answer:
  - Both
    - Put the first few parameters in registers (if they fit) (X0 – X7)
    - Put the rest in memory on the call stack— important concept

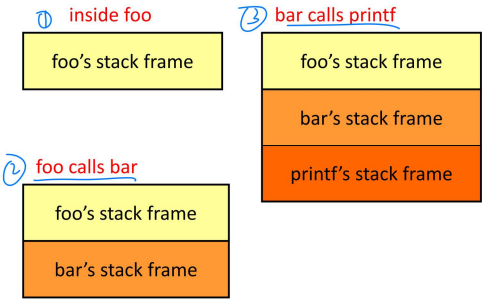
Call stack

- ARM conventions (and most other processors) allocate a region of memory for the "call" stack
  - This memory is used to manage all the storage requirements to simulate function call semantics
    - Parameters (that were not passed through registers)
    - Local variables
    - Temporary storage (when you run out of registers and need somewhere to save a value)
    - Return address
    - Etc.
- Sections of memory on the call stack [**stack frames**] are allocated when you make a function call, and de-allocated when you return from a function

The stack grows as functions are called

FUNCTION CALLS

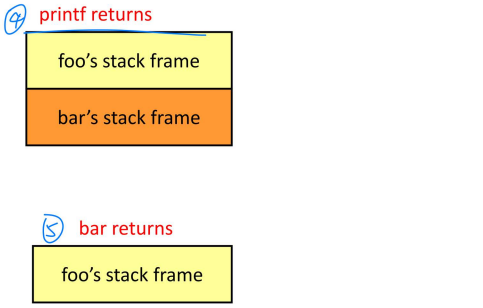
```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```



The stack shrinks as functions return

FUNCTION CALLS

```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```

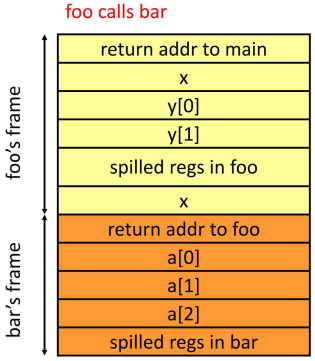


Stack frame contents (2)

FUNCTION CALLS

```
void foo()
{
  int x, y[2];
  bar(x);
}

void bar(int x)
{
  int a[3];
  printf();
}
```

Spill data—not enough room in x0-x7 for params and also caller and callee saves



Agenda

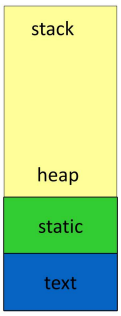
- Using branches more generally
- Function calls and the call stack
- **Assigning variables to memory locations**
- Saving registers
- Caller/callee example

Review: Where do the variables go?

Assigning variables to memory spaces

FUNCTION CALLS

```
int w;
void foo(int x)
{
  static int y[4];
  char* p;
  p = malloc(10);
  //…
  printf("%s\n", p);
}
```



Assigning variables to memory spaces

FUNCTION CALLS

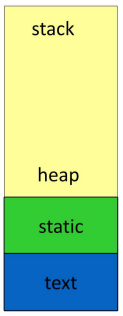
```
int w;
void foo(int x)
{
  static int y[4];
  char* p;
  p = malloc(10);
  //…
  printf("%s\n", p);
}
```

w goes in static, as it's a global
x goes on the stack, as it's a parameter

y goes in static, 1 copy of this!!
p goes on the stack
allocate 10 bytes on heap, ptr set to the address

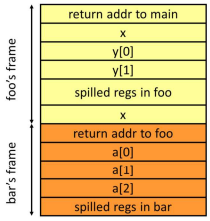
string literal "%s\n" goes in static, implicit pointer to string on stack, p goes on stack

The addresses of local variables will be different depending on where we are in the call stack



Accessing Local Variables

- Stack pointer (SP):
  - register that keeps track of current top of stack
- Compiler (or assembly writer) knows relative offsets of objects in stack
- Can access using lw/sw offsets



Agenda

- Using branches more generally
- Function calls and the call stack
- Assigning variables to memory locations
- **Saving registers**
- Caller/callee example

What about registers?

- Higher level languages (like C/C++) provide many abstractions that don't exist at the assembly level
- E.g. in C, each function has its own local variables
  - Even if different function have local variables with the same name, they are independent and guaranteed not to interfere with each other!

```
void foo(){
  int a=1;
  bar();
  printf(a);
}
```

Still prints "1"... these don't interfere

```
void bar(){
  int a=2;
  return;
}
```


What about registers?

- But in assembly, all functions share a small set (e.g. 32) of registers
  - Called functions will overwrite registers needed by calling functions

```
main: movz X0, #1
      bl foo
      bl printf
```

foo() overwrites X0 if we don't do something!!

```
foo: movz X0, #2
     br X30
```

- "Someone" needs to save/restore values when a function is called to ensure this doesn't happen

Two Possible Solutions

- Either the **called** function saves register values before it overwrites them and restores them before the function returns (**callee** saved)…

```
main: movz X0, #1
      bl foo
      bl printf
```

```
foo: stur X0, [stack]
     movz X0, #2
     ldur X0, [stack]
     br X30
```

- Or the **calling** function saves register values before the function call and restores them after the function call (**caller** saved)…

```
main: movz X0, #1
      stur X0, [stack]
      bl foo
      ldur X0, [stack]
      bl printf
```

```
foo: movz X0, #2
     br X30
```


a->r1, b->r2, etc.

Another example

Original C Code

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;

  bar();

  d = a+d;
  return();
}
```

No need to save r2/r3. Why?

Additions for Caller-save

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;
  save r1 to stack
  save r4 to stack
  bar();
  restore r4
  restore r1
  d = a+d;
  return();
}
```

Assume bar() will overwrite registers holding a,d

Additions for Callee-save

```
void foo(){
  int a,b,c,d;
  save r1
  save r2
  save r3
  save r4
  a = 5; b = 6;
  c = a+1; d=c-1;
  bar();
  d = a+d;
  restore r4
  restore r3
  restore r2
  restore r1
  return();
}
```

bar() will save a,b, but now foo() must save main's variables

"caller-save" vs. "callee-save"

- Caller-save
  - What if bar() doesn't use r1/r4?
  - No harm done, but wasted work

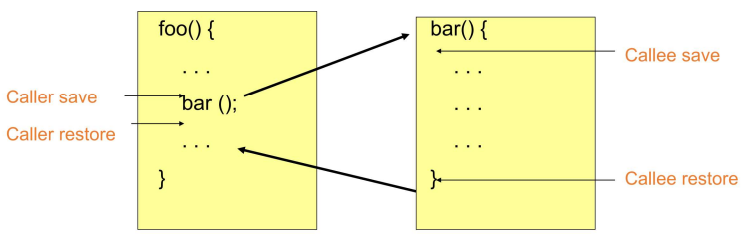
```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;
  save r1 to stack
  save r4 to stack
  bar();
  restore r1
  restore r4
  d = a+d;
  return();
}
```

- Callee-save
  - What if main() doesn't use r1-r4?
  - No harm done, but wasted work

```
void foo(){
  int a,b,c,d;
  save r1
  save r2
  save r3
  save r4
  a = 5; b = 6;
  c = a+1; d=c-1;
  bar();
  d = a+d;
  restore r1
  restore r2
  restore r3
  restore r4
  return();
}
```


Another helpful visual

CALLER-CALLEE



Saving/Restoring Optimizations

CALLER-CALLEE

- Where can we avoid loads/stores?
- Caller-saved
  - Only needs saving if value is "live" across function call
  - Live = contains a useful value: Assign value before function call, use that value after the function call
  - In a leaf function (a function that calls no other function), caller saves can be used without saving/restoring

a, d are live

b, c are NOT live

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;

  bar();

  d = a+d;
  return();
}
```


Saving/Restoring Optimizations

CALLER-CALLEE

- Where can we avoid loads/stores?
- Callee-saved
  - Only needs saving at beginning of function and restoring at end of function
  - Only save/restore it if function overwrites the register

Only use r1-r4

No need to save other registers

```
void foo(){
  int a,b,c,d;

  a = 5; b = 6;
  c = a+1; d=c-1;

  bar();

  d = a+d;
  return();
}
```


Agenda

- Using branches more generally
- Function calls and the call stack
- Assigning variables to memory locations
- Saving registers
- **Caller/callee example**

Caller versus Callee

- Which is better??
- Let's look at some examples…

- Simplifying assumptions:
  - A function can be invoked by many different call sites in different functions.
  - Assume no inter-procedural analysis (hard problem)
    - A function has no knowledge about which registers are used in either its caller or callee
    - Assume main() is not invoked by another function
  - Implication
    - Any register allocation optimization is done using function local information

Caller-saved vs. callee saved – Multiple function case

```
void main(){
  int a,b,c,d;

  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;

}
```

```
void foo(){
  int e,f;

  e = 2; f = 3;
  bar();
  e = e + f;

}
```

```
void bar(){
  int g,h,i,j;

  g = 0; h = 1;
  i = 2; j = 3;
  final();
  j = g+h+i;

}
```

```
void final(){
  int y,z;

  y = 2; z = 3;

  z = y+z;

}
```

Note: assume main does not have to save any callee registers

Caller-saved vs. callee saved – Multiple function case

- Questions:
1. How many registers need to be saved/restored if we use a **caller-save** convention?
2. How many registers need to be saved/restored if we use a **callee-save** convention?
3. How many registers need to be saved/restored if we use a mix of **caller-save** and **callee-save**?

Question 1: Caller-save

Poll: How many ld/st pairs are needed?

```
void main(){
  int a,b,c,d;
  c = 5; d = 6;
  a = 2; b = 3;
  [4 STUR]
  foo();
  [4 LDUR]
  d = a+b+c+d;

}
```

```
void foo(){
  int e,f;

  e = 2; f = 3;
  [2 STUR]
  bar();
  [2 LDUR]
  e = e + f;

}
```

```
void bar(){
  int g,h,i,j;
  g = 0; h = 1;
  i = 2; j = 3;
  [3 STUR]
  final();
  [3 LDUR]
  j = g+h+i;

}
```

```
void final(){
  int y,z;


  y = 2; z = 3;

  z = y+z;


}
```

Total: 9 STUR / 9 LDUR

Question 2: Callee-save

Poll: How many ld/st pairs are needed?

```
void main(){
  int a,b,c,d;

  c = 5; d = 6;
  a = 2; b = 3;
  foo();
  d = a+b+c+d;


}
```

```
void foo(){
  [2 STUR]
  int e,f;

  e = 2; f = 3;
  bar();
  e = e + f;

  [2 LDUR]
}
```

```
void bar(){
  [4 STUR]
  int g,h,i,j;
  g = 0; h = 1;
  i = 2; j = 3;
  final();
  j = g+h+i;

  [4 LDUR]
}
```

```
void final(){
  [2 STUR]
  int y,z;


  y = 2; z = 3;

  z = y+z;


  [2 LDUR]
}
```

Total: 8 STUR / 8 LDUR

Is one better?

- Caller-save works best when we don't have many live values across function call
- Callee-save works best when we don't use many registers overall
- We probably see functions of both kinds across an entire program
- Solution:
  - Use both!
  - E.g. if we have 6 registers, use some (say r0-r2) as caller-save and others (say r3-r5) as callee-save
  - Now each function can optimize for each situation to reduce saving/restoring

Poll: What's the optimal number of caller/callee registers for final?

Question 3: Mixed 3 caller / 3 callee

- For main, ideally put all variables in callee-save registers
- But we only 3 are available
- One variable needs to go in caller-saved register

```
void main(){
  int a,b,c,d;
  c = 5; d = 6;
  a = 2; b = 3;
  [1 STUR]
  foo();
  [1 LDUR]
  d = a+b+c+d;
}
```

1 caller r
3 callee r

```
void foo(){
  [2 STUR]
  int e,f;

  e = 2; f = 3;
  bar();
  e = e + f;

  [2 LDUR]
}
```

2 callee r
(2 caller would be equivalent)

```
void bar(){
  [3 STUR]
  int g,h,i,j;
  g = 0; h = 1;
  i = 2; j = 3;
  final();
  j = g+h+i;

  [3 LDUR]
}
```

1 caller r
3 callee r

```
void final(){
  int y,z;


  y = 2; z = 3;

  z = y+z;


}
```

2 caller r

Total: 6 STUR / 6 LDUR

LEGv8 ABI- Application Binary Interface

- The ABI is an agreement about how to use the various registers
- Not enforced by hardware, just a convention by programmers / compilers
- If you won't your code to work with other functions / libraries, **follow these**
- Some register conventions in ARMv8
  - X30 is the **link register** – used to hold return address
  - X28 is **stack pointer** – holds address of top of stack
  - X19-X27 are **callee-saved** – function must save these before writing to them
  - X0-15 are **caller-saved** –function must save live values before call
  - X0-X7 used for **arguments** (memory used if more space is needed)
  - X0 used for **return value**

Next Time

- Finish Up Function Calls
- Talks about linking – the final puzzle piece of software