Topic 7: Control Flow Instructions

CSE 30: Computer Organization and Systems Programming
Summer Session II

Dr. Ali Irturk
Dept. of Computer Science and Engineering
University of California, San Diego

So Far…

- All instructions have allowed us to manipulate data
- So we’ve built a calculator
- In order to build a computer, we need ability to make decisions…

Labels

- Any instruction can be associated with a label
- Example:

```
start ADD r0,r1,r2 ; a = b+c
next  SUB r1,r1,#1 ; b--
```

- In fact, every instruction has a label regardless if the programmer explicitly names it
  - The label is the address of the instruction
  - A label is a pointer to the instruction in memory
  - Therefore, the text label doesn't exist in binary code

C Decisions: `if` Statements

- `if` statements in C
  - `if (`*condition*`)` *clause*
  - `if (`*condition*`)` *clause1* `else` *clause2*
- Rearrange 2nd `if` into following:

```
if (condition) goto L1;
     clause2;
     goto L2;
 L1: clause1;
 L2:
```

  - Not as elegant as if-else, but same meaning

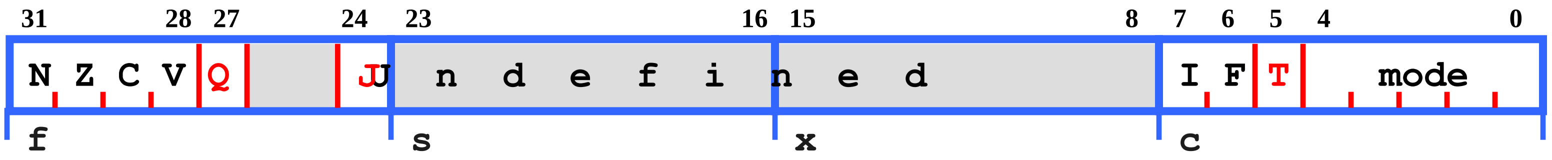
ARM goto Instruction

- The simplest control instruction is equivalent to a C `goto` statement
- `goto label` (in C) is the same as:
- `B label` (in ARM)
- `B` is shorthand for “branch”. This is called an unconditional branch meaning that the branch is done regardless of any conditions.
- There are also conditional branches

ARM Decision Instructions

- ARM also has variants of the branch instruction that only goto the label if a certain condition is TRUE
- Examples:
  - `BEQ label ; BRANCH EQUAL`
  - `BNE label ; BRANCH NOT EQUAL`
  - `BLE label ; BRANCH LESS THAN EQUAL`
  - `BLT label ; BRANCH LESS THAN`
  - `BGE label ; BRANCH GREATER THAN EQUAL`
  - `BGT label ; BRANCH GREATER THAN`
  - Plus more …
- The condition is T/F based upon the fields in the Program Status Register

Program Status Registers



- Condition code flags
  - N = **N**egative result from ALU
  - Z = **Z**ero result from ALU
  - C = ALU operation **C**arried out
  - V = ALU operation o**V**erflowed
- Sticky Overflow flag - Q flag
  - Architecture 5TE/J only
  - Indicates if saturation has occurred
- J bit
  - Architecture 5TEJ only
  - J = 1: Processor in Jazelle state
- Interrupt Disable bits.
  - I = 1: Disables the IRQ.
  - F = 1: Disables the FIQ.
- T Bit
  - Architecture xT only
  - T = 0: Processor in ARM state
  - T = 1: Processor in Thumb state
- Mode bits
  - Specify the processor mode

Flags and Their Use

- The N flag
  - Set if the result is negative or equivalently if the MSB == ‘1’
- The Z flag
  - Set if the result is zero
- The C flag
  - Set if
    - The result of an addition is greater than 2^{32}
    - The result of a subtraction is positive
    - Carryout from the shifter is ‘1’
- The V flag (oVerflow)
  - Set if there is overflow

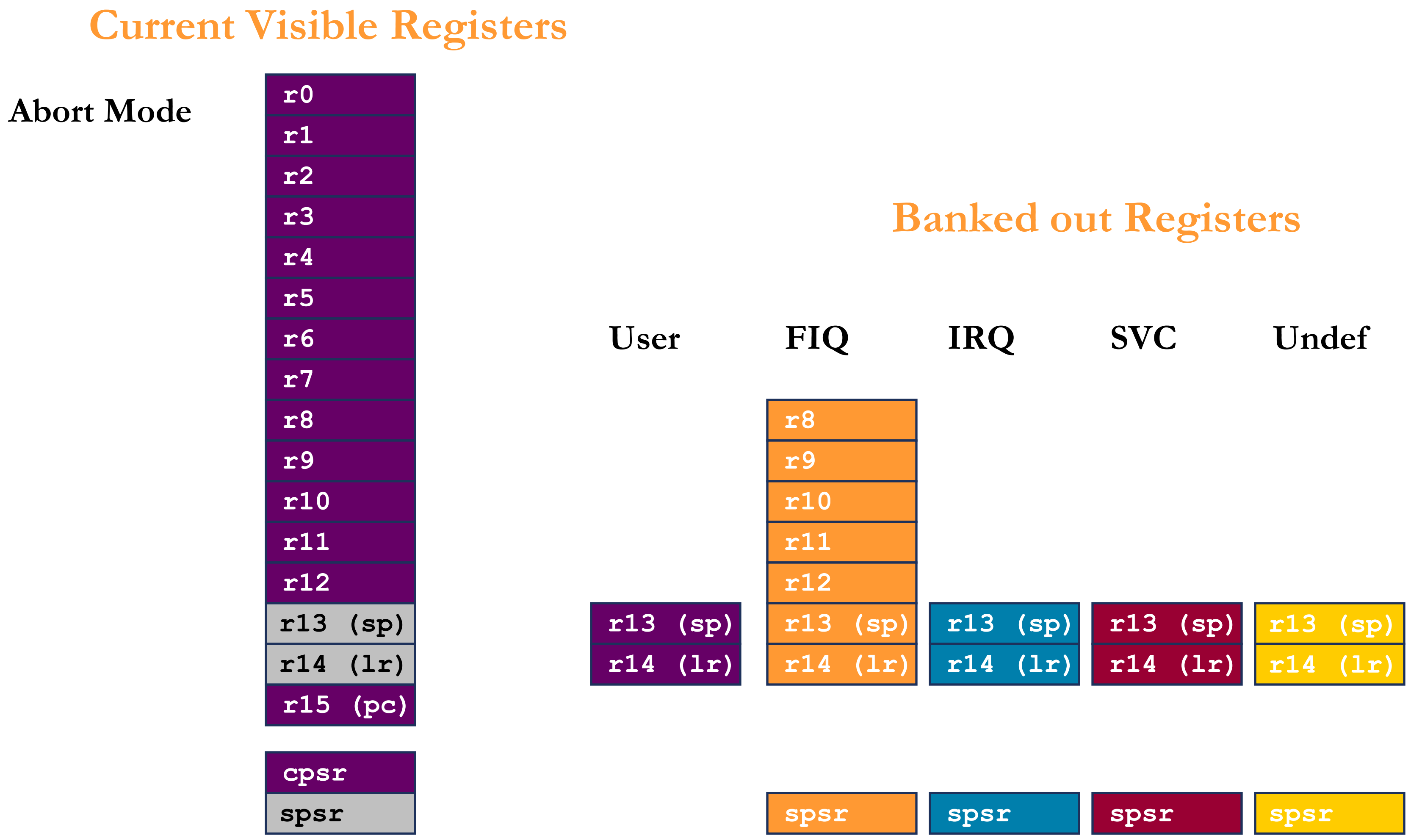
Condition Codes

- The possible condition codes are listed below
  - Note AL is the default and does not need to be specified

Suffix	Description	Flags tested
`EQ`	Equal	Z=1
`NE`	Not equal	Z=0
`CS/HS`	Unsigned higher or same	C=1
`CC/LO`	Unsigned lower	C=0
`MI`	Minus	N=1
`PL`	Positive or Zero	N=0
`VS`	Overflow	V=1
`VC`	No overflow	V=0
`HI`	Unsigned higher	C=1 & Z=0
`LS`	Unsigned lower or same	C=0 or Z=1
`GE`	Greater or equal	N=V
`LT`	Less than	N!=V
`GT`	Greater than	Z=0 & N=V
`LE`	Less than or equal	Z=1 or N=!V
`AL`	Always	

The ARM Register Set

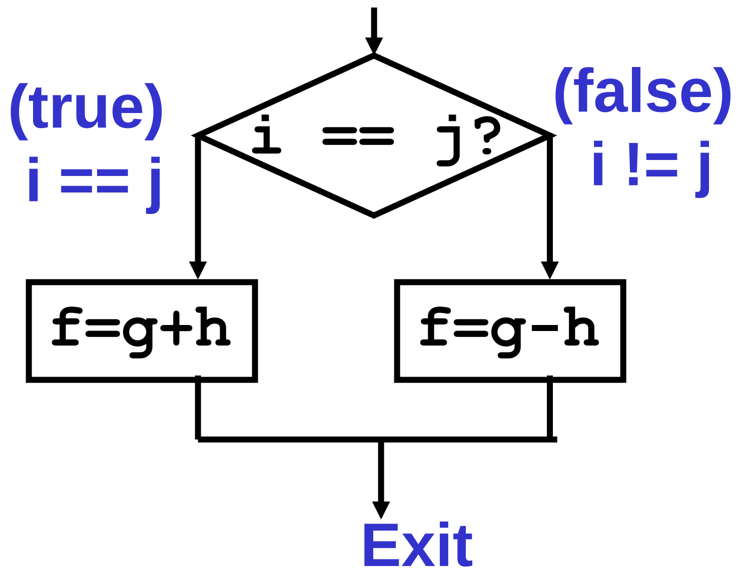
Only need to worry about cpsr (current program status register)



Compiling C `if` into ARM

- Compile by hand

```
if (i == j) f=g+h;
else f=g-h;
```



- Use this mapping:

```
f: r0, g: r1, h: r2, i: r3, j: r4
```

Comparison Instructions

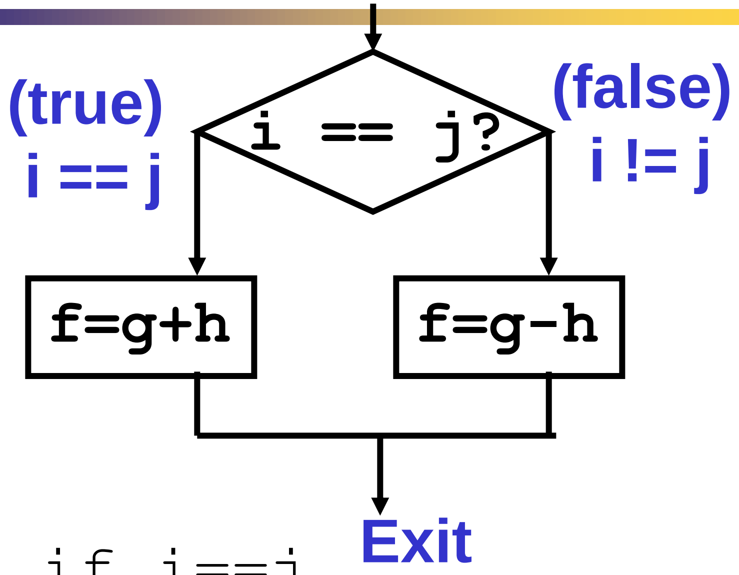
- In order to perform branch on the “==“ operation we need a new instruction
- `CMP` – Compare: subtracts a register or an immediate value from a register value and updates condition codes
- Examples:
  - `CMP r3, #0 ; set Z flag if r3 == 0`
  - `CMP r3, r4 ; set Z flag if r3 == r4`

All flags are set as result of this operation, not just Z.

Compiling C `if` into ARM

Compile by hand

```
if (i == j) f=g+h;
else f=g-h;
```



❖ Final compiled MIPS code:

```
     CMP  r3, r4     ; Z = 1 if i==j
     BEQ  True       ; goto True when i==j
     SUB  r0,r1,r2   ; f=g-h(false)
     B    Fin        ; goto Fin
True ADD r0,r1,r2    ; f=g+h (true)
Fin
```

Note: Compiler automatically creates labels to handle decisions (branches) appropriately. Generally not found in C code.

Loops in C/Assembly

- Simple loop in C;

```
do{
   g--;
   i = i + j;}
while (i != h);
```

- Rewrite this as:

```
 Loop: g--;
       i = i + j;
       if (i != h) goto Loop;
```

- Use this mapping:

```
g: r1, h: r2, i: r3, j: r4
```

Loops in C/Assembly

- Final compiled MIPS code:

```
Loop    SUB r1,r1,#1     ; g--
        ADD r3,r3,r4     ; i=i+j
        CMP r3,r2        ; cmp i,h
        BNE Loop         ; goto Loop
                         ; if i!=h
```

Inequalities in ARM

- Until now, we've only tested equalities (== and != in C). General programs need to test < and > as well.
- Use `CMP` and `BLE, BLT, BGE, BGT`
- Examples:

```
if (f < 10) goto Loop; =>    CMP r0,#10
                             BLT Loop
if (f >= i) goto Loop; =>    CMP r0,r3
                             BGE Loop
```

Loops in C/Assembly

- There are three types of loops in C:
  - `while`
  - `do… while`
  - `for`
- Each can be rewritten as either of the other two, so the method used in the previous example can be applied to `while` and `for` loops as well.
- Key Concept: Though there are multiple ways of writing a loop in ARM, conditional branch is key to decision making

Example: The C Switch Statement

- Choose among four alternatives depending on whether `k` has the value 0, 1, 2 or 3. Compile this C code:

```
switch (k) {
   case 0: f=i+j; break; /* k=0*/
   case 1: f=g+h; break; /* k=1*/
   case 2: f=g-h; break; /* k=2*/
   case 3: f=i-j; break; /* k=3*/
   }
```

Example: The C Switch Statement

- This is complicated, so simplify.
- Rewrite it as a chain of if-else statements, which we already know how to compile:

```
if(k==0) f=i+j;
  else if(k==1) f=g+h;
    else if(k==2) f=g-h;
      else if(k==3) f=i-j;
```

- Use this mapping:

```
f: $s0, g: $s1, h: $s2, i: $s3,
 j: $s4, k: $s5
```

Example: The C Switch Statement

```
     CMP r5,#0        ; compare k, 0
     BNE L1           ; branch k!=0
     ADD r0,r3,r4     ; k==0 so f=i+j
     B   Exit         ; end of case so Exit
L1   CMP r5,#1        ; compare k, -1
     BNE L2
     ADD r0,r1,r2     ; k==1 so f=g+h
     B   Exit         ; end of case so Exit
L2   CMP r5,#2        ; compare k, 2
     BNE L3           ; branch k!=2
     SUB r0,r1,r2     ; k==2 so f=g-h
     B   Exit         ; end of case so Exit
L3   CMP r5,#3        ; compare k, 3
     BNE Exit         ; branch k!=3
     SUB r0,r3,r4     ; k==3 so f=i-j
Exit
```

Predicated Instructions

- All instructions can be executed conditionally. Simply add {EQ,NE,LT,LE,GT,GE, etc.} to end

C source code

```
if (r0 == 0)
{
  r1 = r1 + 1;
}
else
{
  r2 = r2 + 1;
}
```

ARM instructions

unconditional

```
   CMP r0, #0
   BNE else
   ADD r1, r1, #1
   B end
else
   ADD r2, r2, #1
end
   ...
```

- 5 instructions
- 5 words
- 5 or 6 cycles

conditional

```
   CMP r0, #0
   ADDEQ r1, r1, #1
   ADDNE r2, r2, #1
   ...
```

- 3 instructions
- 3 words
- 3 cycles

Conclusions

- A Decision allows us to decide which pieces of code to execute at run-time rather than at compile-time.
- C Decisions are made using conditional statements within an `if`, `while`, `do while` or `for`.
- `CMP` instruction sets status register bits
- ARM Decision making instructions are the conditional branches: `BNE,BEQ,BLE,BLT,BGE,BGT`.

Conclusion

- Instructions so far:
  - Previously:

```
ADD, SUB, MUL, MULA, [U|S]MULL, [U|S]MLAL, RSB
AND, ORR, EOR, BIC
MOV, MVN
LSL, LSR, ASR, ROR
```

  - New:

```
CMP, B{EQ,NE,LT,LE,GT,GE}
```