Dreamworks today released their big fall movie. Pixar will release their movie “The Incredibles” soon. Compare & contrast the two!

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I-Format Problems (0/3)

• Problem 0: Unsigned # sign-extended?
  • addiu, sltiu, **sign-extends** immediates to 32 bits. Thus, # is a “signed” integer.

• Rationale
  • addiu so that can add w/out overflow
    - See K&R pp. 230, 305
  • sltiu suffers so that we can have ez HW
    - Does this mean we’ll get wrong answers?
    - Nope, it means assembler has to handle any unsigned immediate $2^{15} \leq n < 2^{16}$ (i.e., with a 1 in the 15th bit and 0s in the upper 2 bytes) as it does for numbers that are too large. ⇒
I-Format Problems (1/3)

• Problem 1:
  • Chances are that addi, lw, sw and slti will use immediates small enough to fit in the immediate field.
  • …but what if it’s too big?
  • We need a way to deal with a 32-bit immediate in any I-format instruction.
I-Format Problems (2/3)

• Solution to Problem 1:
  • Handle it in software + new instruction
  • Don’t change the current instructions: instead, add a new instruction to help out

• New instruction:
  lui register, immediate
  • stands for Load Upper Immediate
  • takes 16-bit immediate and puts these bits in the upper half (high order half) of the specified register
  • sets lower half to 0s
I-Format Problems (3/3)

- Solution to Problem 1 (continued):
  - So how does \texttt{lui} help us?
  - Example:
    
    \[
    \text{addi} \quad \$t0,\$t0, \ 0x\text{ABABCDCD} \\
    \text{becomes:} \\
    \text{lui} \quad \$at, \ 0x\text{ABAB} \\
    \text{ori} \quad \$at, \$at, \ 0xCDCD \\
    \text{add} \quad \$t0,\$t0,\$at
    \]

- Now each I-format instruction has only a 16-bit immediate.

- Wouldn’t it be nice if the assembler would do this for us automatically? (later)
Branches: PC-Relative Addressing (1/5)

- Use I-Format

<table>
<thead>
<tr>
<th>opcode</th>
<th>rs</th>
<th>rt</th>
<th>immediate</th>
</tr>
</thead>
</table>

- opcode specifies beq v. bne
- rs and rt specify registers to compare
- What can immediate specify?
  - Immediate is only 16 bits
  - PC (Program Counter) has byte address of current instruction being executed; 32-bit pointer to memory
  - So immediate cannot specify entire address to branch to.
Branches: PC-Relative Addressing (2/5)

- How do we usually use branches?
  - Answer: if-else, while, for
  - Loops are generally small: typically up to 50 instructions
  - Function calls and unconditional jumps are done using jump instructions (j and jal), not the branches.

- Conclusion: may want to branch to anywhere in memory, but a branch often changes PC by a small amount
Branches: PC-Relative Addressing (3/5)

• Solution to branches in a 32-bit instruction: **PC-Relative Addressing**

• Let the 16-bit immediate field be a signed two’s complement integer to be *added* to the PC if we take the branch.

• Now we can branch $\pm 2^{15}$ bytes from the PC, which should be enough to cover almost any loop.

• Any ideas to further optimize this?
Branches: PC-Relative Addressing (4/5)

• Note: Instructions are words, so they’re word aligned (byte address is always a multiple of 4, which means it ends with 00 in binary).
  • So the number of bytes to add to the PC will always be a multiple of 4.
  • So specify the immediate in words.

• Now, we can branch $\pm 2^{15}$ words from the PC (or $\pm 2^{17}$ bytes), so we can handle loops 4 times as large.
Branches: PC-Relative Addressing (5/5)

• Branch Calculation:
  - If we don’t take the branch:
    \[ PC = PC + 4 \]
    \[ PC+4 = \text{byte address of next instruction} \]
  - If we do take the branch:
    \[ PC = (PC + 4) + (\text{immediate} \times 4) \]

• Observations
  - Immediate field specifies the number of words to jump, which is simply the number of instructions to jump.
  - Immediate field can be positive or negative.
  - Due to hardware, add immediate to (PC+4), not to PC; will be clearer why later in course
Branch Example (1/3)

• MIPS Code:

```
Loop:       beq    $9,$0, End
            add    $8,$8,$10
            addi   $9,$9,-1
            j      Loop
End:
```

• `beq` branch is I-Format:
  
  - `opcode` = 4 (look up in table)
  - `rs` = 9 (first operand)
  - `rt` = 0 (second operand)
  - `immediate` = ???
Branch Example (2/3)

• MIPS Code:

    Loop: beq $9,$0, End
        addi $8,$8,$10
        addi $9,$9,−1
        j Loop

    End:

• Immediate Field:
  • Number of instructions to add to (or subtract from) the PC, starting at the instruction following the branch.
  • In beq case, immediate = 3
Branch Example (3/3)

• MIPS Code:

    Loop: beq $9,$0,End
        addi $8,$8,$10
        addi $9,$9,-1
        j Loop

    End:

decimal representation:

<table>
<thead>
<tr>
<th>4</th>
<th>9</th>
<th>0</th>
<th>3</th>
</tr>
</thead>
</table>

binary representation:

| 00010001 | 01001 | 00000 | 0000000000000001 |
Questions on PC-addressing

• Does the value in branch field change if we move the code?

• What do we do if destination is $> 2^{15}$ instructions away from branch?

• Since it’s limited to $\pm 2^{15}$ instructions, doesn’t this generate lots of extra MIPS instructions?

• Why do we need all these addressing modes? Why not just one?
J-Format Instructions (1/5)

• For branches, we assumed that we won’t want to branch too far, so we can specify *change* in PC.

• For general jumps (j and jal), we may jump to *anywhere* in memory.

• Ideally, we could specify a 32-bit memory address to jump to.

• Unfortunately, we can’t fit both a 6-bit opcode and a 32-bit address into a single 32-bit word, so we compromise.
J-Format Instructions (2/5)

• Define “fields” of the following number of bits each:

| 6 bits | 26 bits |

• As usual, each field has a name:

| opcode | target address |

• Key Concepts
  • Keep opcode field identical to R-format and I-format for consistency.
  • Combine all other fields to make room for large target address.
J-Format Instructions (3/5)

• For now, we can specify 26 bits of the 32-bit bit address.

• Optimization:
  - Note that, just like with branches, jumps will only jump to word aligned addresses, so last two bits are always 00 (in binary).
  - So let’s just take this for granted and not even specify them.
J-Format Instructions (4/5)

• Now specify 28 bits of a 32-bit address

• Where do we get the other 4 bits?
  • By definition, take the 4 highest order bits from the PC.
  • Technically, this means that we cannot jump to anywhere in memory, but it’s adequate 99.9999...% of the time, since programs aren’t that long
    - only if straddle a 256 MB boundary
  • If we absolutely need to specify a 32-bit address, we can always put it in a register and use the jr instruction.
J-Format Instructions (5/5)

• Summary:
  • New PC = \{ PC[31..28], target address, 00 \}

• Understand where each part came from!

• Note: \{ , , \} means concatenation
  \{ 4 bits , 26 bits , 2 bits \} = 32 bit address
  • \{ 1010, 111111111111111111111111111111, 00 \} = 10101111111111111111111111111100

• Note: Book uses ||, Verilog uses \{ , , \}

• We will learn Verilog later in this class
(for A,B) When combining two C files into one executable, recall we can compile them independently & then merge them together.

A. Jump insts don’t require any changes.
B. Branch insts don’t require any changes.
C. You now have all the tools to be able to “decompile” a stream of 1s and 0s into C!
In conclusion...

- **MIPS Machine Language Instruction**: 32 bits representing a single instruction

<table>
<thead>
<tr>
<th>R</th>
<th>opcode</th>
<th>rs</th>
<th>rt</th>
<th>rd</th>
<th>shamt</th>
<th>funct</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>opcode</td>
<td>rs</td>
<td>rt</td>
<td></td>
<td></td>
<td>immediate</td>
</tr>
<tr>
<td>J</td>
<td>opcode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>target address</td>
</tr>
</tbody>
</table>

- Branches use PC-relative addressing, Jumps use absolute addressing.

- Disassembly is simple and starts by decoding opcode field. (more in a week)