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How to represent \((x<10 \land y>3)\)?

It depends on the target machine

Several approaches:

- Numerical representation
- Positional Encoding (e.g., MIPS assembly)
- Conditional Move and Predication

Correct choice depends on both context and ISA (Instruction Set Architecture)
Numerical Representation

- Assign values to `true` and `false`, usually 1 and 0
- Use comparison operator from the ISA to get a value from a relational expression

**Example**

\[
\begin{align*}
\text{x < y} & \quad \text{@cmp_LT@ rx, ry \rightarrow r1} \\
\text{if (x < y)} & \quad \text{@cmp_LT@ rx, ry \rightarrow r1} \\
\text{stmt1} & \quad \text{cbr r1 \rightarrow L1} \\
\text{else} & \quad \text{stmt2} \\
\text{stmt2} & \quad \text{br \rightarrow Le} \\
\text{L1: stmt1} & \\
\text{Le: } & 
\end{align*}
\]
What if the ISA does not provide comparison operators that returns a value?

- Must use conditional branch to interpret the result of a comparison
- Necessitates branches in the evaluation
- This is the case for MIPS assembly (and Java ByteCode for instance)

Example: \( x < y \)

\[
\begin{align*}
@br & \_LT@ \quad rx, ry \rightarrow L_T \\
load & \quad 0 \rightarrow r1 \\
br & \rightarrow L_E \\
LT: \quad load & \quad 1 \rightarrow r1 \\
LE: & \quad \ldots
\end{align*}
\]
If the result is used to control an operation, then positional encoding is not that bad.

**Example**

```c
if (x < y)
    a = c + d;
else
    a = e + f;
```

**Corresponding assembly code**

<table>
<thead>
<tr>
<th>Boolean comparison</th>
<th>Positional encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>@cmp_LT@ rx, ry→r1</code></td>
<td><code>@br_LT@ rx, ry→L_T</code></td>
</tr>
<tr>
<td><code>cbr r1 →L_T</code></td>
<td><code>add re, rf→ra</code></td>
</tr>
<tr>
<td><code>add re, rf→ra</code></td>
<td><code>br →L_E</code></td>
</tr>
<tr>
<td><code>br →L_E</code></td>
<td><code>LT:add rc, rd→ra</code></td>
</tr>
<tr>
<td><code>LT:add rc, rd→ra</code></td>
<td><code>LE:...</code></td>
</tr>
<tr>
<td><code>LE:...</code></td>
<td><code>LE:...</code></td>
</tr>
</tbody>
</table>
Conditional Move and Predication

Conditional move and predication can simplify this code.

Example

```c
if ( x < y )
  a = c + d;
else
  a = e + f;
```

Corresponding assembly code

<table>
<thead>
<tr>
<th>Conditional Move</th>
<th>Predicated Execution</th>
</tr>
</thead>
<tbody>
<tr>
<td>cmp_LT rx, ry -&gt; r1</td>
<td>cmp_LT rx, ry -&gt; r1</td>
</tr>
<tr>
<td>add rc, rd -&gt; r2</td>
<td>@(r1)?@ add rc, rd -&gt; ra</td>
</tr>
<tr>
<td>add re, rf -&gt; r3</td>
<td>@( ! r1 )?@ add re, rf -&gt; ra</td>
</tr>
<tr>
<td>@cmov@ r1, r2, r3 -&gt; ra</td>
<td></td>
</tr>
</tbody>
</table>
Last word on boolean and relational values: consider the following code
\[ x = (a < b) \land (c < d) \]

**Corresponding assembly code**

<table>
<thead>
<tr>
<th>Positional encoding</th>
<th>Boolean Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>\texttt{br_LT ra, rb} \rightarrow L_1</td>
<td>\texttt{cmp_LT ra, rb} \rightarrow r1</td>
</tr>
<tr>
<td>\texttt{br} \rightarrow L_2</td>
<td>\texttt{cmp_LT rc, rd} \rightarrow r2</td>
</tr>
<tr>
<td>\text{L}_1: \texttt{br_LT rc, rd} \rightarrow L_3</td>
<td>\text{and} r1, r2 \rightarrow rx</td>
</tr>
<tr>
<td>\text{L}_2: \texttt{loadl} 0 \rightarrow rx</td>
<td></td>
</tr>
<tr>
<td>\texttt{br} \rightarrow Le</td>
<td></td>
</tr>
<tr>
<td>\text{L}_3: \texttt{loadl} 1 \rightarrow rx</td>
<td></td>
</tr>
<tr>
<td>\text{L}_e: \ldots</td>
<td></td>
</tr>
</tbody>
</table>

Here the boolean comparison produces much better code.

**Best choice depends on two things**

- Context
- Hardware
Control-Flow

- If-then-else
- Loops (for, while, …)
- Switch/case statements
If-then-else

Follow the model for evaluating relational and boolean with branches.

Branching versus predication (e.g., IA-64, ARM ISA) trade-off:
- Frequency of execution:
  uneven distribution, try to speedup common case
- Amount of code in each case:
  unequal amounts means predication might waste issue slots
- Nested control flow:
  any nested branches complicates the predicates and makes branching attractive
Loops

Basic pattern

- evaluate condition before the loop (if needed)
- evaluate condition after the loop
- branch back to the top (if needed)

while, for and do while loops all fit this basic model.
Example: for loop

```c
for (i=1; i<100; i++) {
    @body@
}
@next stmt@
```

Corresponding assembly

```
loadl 1 → r1
loadl 100 → r2
br_GT r1, r2 → L2
L1:   @body@
    addl r1, 1 → r1
    br_LT r1, r2 → L1
L2:   @next stmt@
```
Exercise

Write the assembly code for the following while loop:

```plaintext
while (x >= y) {
    body
}
next stmt
```
Most modern programming languages include a `break` statements

- Exits from the innermost control-flow statement
  - Out of the innermost loop
  - Out of a case statement

Solution:

- use an unconditional branch to the next statement following the control-flow construct (loop or case statement).
- **skip** or **continue** statement branch to the next iteration (start of the loop)
Case Statement (switch)

Case statement

```
switch (c) {
    case 'a': stmt1;
    case 'b': stmt2; break;
    case 'c': stmt3;
}
```

1. Evaluate the controlling expression
2. Branch to the selected case
3. Execute the code for that case
4. Branch to the statement after the case

Part 2 is key.

Strategies:
- Linear search (nested if-then-else)
- Build a table of case expressions and use binary search on it
- Directly compute an address (requires dense case set)
Exercise

Knowing that the character ‘a’ corresponds to the decimal value 97 (ASCII table), write the assembly code for the example below using linear search.

```c
char c;
...
switch (c) {
    case 'a': stmt1;
    case 'b': stmt2; break;
    case 'c': stmt3; break;
    case 'd': stmt4;
}
stmt5;
```

Exercise: can you do it without any conditional jumps?

Hint: use the JR MIPS instruction which jumps directly to an address stored in a register.
Static versus Dynamic

- **Static allocation**: storage can be allocated directly by the compiler by simply looking at the program at compile-time. This implies that the compiler can infer storage size information.

- **Dynamic allocation**: storage needs to be allocated at run-time due to unknown size or function calls.
Heap, Stack, Static storage

Static storage:
- Text: contains the instructions
- Data: contains statically allocated data (e.g., global variables, string literals, global arrays of fixed size)

Dynamic Storage:
- Stack: used for function calls, used for local variables (if known size), register spilling (register allocation)
- Heap: used for dynamic allocation (e.g., malloc)
Example

```c
char c;          // data
int arr[4];     // data
void foo() {
    int arr2[3]; // stack
    int* ptr = (int*) malloc(sizeof(int)*2);
    ...{
        int b;    // stack
        ...
        bar("hello"); // data
    }
    ...
}
```

![Memory Management Diagram]
Typically
- `int` and pointer types (e.g., `char*`, `int*`, `void*`) are 32 bits (4 byte).
- `char` is 1 byte

However, it depends on the data alignment of the architecture. For instance, `char` typically occupies 4 bytes on the stack (if the data alignment is 4 bytes).
In a C structure, all values are aligned to the data alignment of the architecture (unless packed directive is used).

```c
struct myStruct_t {
    char c;
    int x;
};
struct myStruct_t ms;
...
```

In this example, it is as if the value c uses 4 bytes of data.

```assembly
.data
ms_myStruct_t_c: .space 4
ms_myStruct_t_x: .space 4
.text
...
```
The compiler needs to keep track of where variables are allocated on the stack.

- **Problem:** stack pointer can move.
- **Solution:** use another pointer, the *frame pointer*

**Frame pointer**

- The frame pointer must be initialised to the value of the stack pointer, just when entering the function (in the prologue).
- Access to variables allocated on the stack can then be determined as a fixed offset from the frame pointer.
The frame pointer (FP) always points to the beginning of the local variables of the current function, just after the arguments (if any).

The stack pointer (SP) always points at the bottom of the stack, where memory is free (the stack grows downwards).
Function calls

What happens during a function call?

- The caller needs to pass the arguments to the callee
- The callee needs to pass the return value to the caller

But also:

- The values stored in temporaries registers needs to be saved somehow.
- Need to remember where we came from so that we can return to the call site.
General convention:

- **precall**: pass the arguments via dedicated registers or stack
- **postreturn**: read the return value from dedicated register or stack
- **prologue**: initialised the frame pointer and save all the temporary registers onto the stack
- **epilogue**: restore all the temporary registers from the stack

Other convention possible but may lead to larger code size.
Example

```c
int bar(int a) {
    return 3 + a;
}
```

```assembly
bar:
    addi $sp, $sp, -4  # decrement stack pointer by 4
    sw $t0, 0($sp)    # save $t0 onto the stack
    li $t0, 3         # load 3 into $t0
    add $t0, $a0, $t0 # add $t0 and first argument
    add $v0, $zero, $t0 # copy the result in return register
    lw $t0, 0($sp)    # restore original $t0 from stack
    addi $sp, $sp, 4  # increment stack pointer by 4
    jr $ra             # jumps to return address
```
Example

```c
void foo() {
    ...
    bar(4)
    ...
}

foo:
    ...

li $t0, 4 # store 4 into $t0
add $a0, $zero, $t0 # copy value into argument register
jal bar # jump and link (ra=PC+8)
add $t0, $zero, $v0 # copy returned value to $t0
    ...
```
Final words

What if need to pass more than 4 arguments (mips only has 4 “argument” registers by convention):

- Use the stack, by pushing the arguments in the precall
- Read the argument from the stack using the frame pointer

What if callee makes a call to another function?

- Need to save the return address of caller and frame pointer on the stack and restore after the call (should be part of precall/postreturn).
Next lecture

Instruction selection

- Peephole Matching
- Tree-pattern matching