USES OF BOOLEAN EXPRESSIONS

Used to drive conditional execution of program sections, e.g.

IF (a < 17) OR (b = 12) THEN ... ELSE ...;

WHILE NOT ((x+1) > 39) DO ... END;

(In some languages) may be assigned to boolean variables or passed as parameters, e.g.:

VAR b : BOOLEAN := (a < 17) OR (b = 12);
...
IF b THEN ... ELSE ...
...
myproc(b); (* procedure call *)
...

SAMPLE PRODUCTIONS FOR VALUE-BASED BOOLEANS

B := E1 '<' E2
B.place = newtemp()
B.code =
let true = newlabel()
  after = newlabel()
in E1.code @
E2.code @
[gen(true,if<,E1.place,E2.place),
gen(B.place,:=,0,_),
gen(after,goto,_,_),
gen(true,:,_,_),
gen(B.place,:=,1,_),
gen(after,:,_,_)]

Generates:

IF E1 < E2 GOTO L1
  T := 0
  GOTO L2
L1: T := 1
L2: ...
MORE SAMPLE VALUE-BASED PRODUCTIONS

\[
B := B_1 \lor B_2 \quad \text{(non-short-circuiting form)}
\]

\[
B\text{.place} = \text{newtemp()}
\]
\[
B\text{.code} = B_1\text{.code} \oplus B_2\text{.code} \oplus \begin{cases} \text{gen}(B\text{.place},|,B_1\text{.place},B_2\text{.place}) & \text{bit-wise OR} \end{cases}
\]

\[
S := \text{IF } B \text{ THEN } S_1 \text{ ELSE } S_2
\]
\[
S\text{.code} = \text{let } false = \text{newlabel()} \quad \begin{cases} \text{after} = \text{newlabel()} & \text{IF } B = 0 \text{ GOTO L1} \end{cases}
\]
\[
in \text{B\text{.code} } @ \begin{cases} \text{gen}(false,if=,B\text{.place},0) & \text{true exit} \\ \text{gen}(after,goto,_,_) & \text{false exit} \\ \text{gen}(false,:,_,_) & \text{true exit} \\ \text{gen}(after,:,_,_) & \text{false exit} \end{cases}
\]

Generates:

\[
\begin{align*}
\text{IF } B = 0 \text{ GOTO L1} \\
& \quad S_1 \\
& \quad \text{GOTO L2} \\
& \quad L1: S_2 \\
& \quad L2: ...
\end{align*}
\]

EXAMPLE VALUE-BASED CODE

\[
\text{IF } (a > 7) \lor (b = 5) \text{ THEN } x = 7 \text{ ELSE } y = 2;
\]
\[
\begin{align*}
t1 & := \text{addr } a \\
t2 & := *t1 \\
t3 & := \text{const 7} \\
\text{if } t2 > t3 & \text{ goto L1} \\
t4 & := \text{const 0} \\
goto & L2 \\
\text{L1: } & \\
t4 & := \text{const 1} \\
&t9 := t4 \mid t8 \\
t9 & := 0 \text{ goto L6} \\
t10 & := \text{const 7} \\
\text{L2: } & \\
t5 & := \text{addr } b \\
t6 & := *t5 \\
t7 & := \text{const 5} \\
\text{if } t5 = t6 & \text{ goto L3} \\
t8 & := \text{const 0} \\
goto & L4 \\
\text{L3: } & \\
t11 & := \text{addr } x \\
&t12 := t1 0 \\
\text{L4: } & \\
t4 & := \text{addr } a \\
t5 & := \text{addr } b \\
t6 & := *t4 \\
t7 & := \text{const 5} \\
\text{if } t5 = t6 & \text{ goto L3} \\
t8 & := \text{const 0} \\
goto & L4 \\
\text{L5: } & \\
t11 & := \text{addr } x \\
*t12 & := t1 0 \\
\text{L6: } & \\
t4 & := \text{addr } a \\
t5 & := \text{addr } b \\
t6 & := *t5 \\
t7 & := \text{const 5} \\
\text{if } t5 = t6 & \text{ goto L3} \\
t8 & := \text{const 0} \\
goto & L4
\end{align*}
\]

BASIC CONTROL-FLOW REPRESENTATION

Idea: Code generated for boolean and relational expressions has true and false “exits”, i.e., code evaluates expression and then jumps to one place if true and another place if false.

- Relational expressions perform test and jump to true or false exit accordingly.
- Boolean variables and constants jump directly to appropriate true or false exit.
- Boolean expressions simply adjust/combine true/false exits of their sub-expressions.
- Conditional statements define true and false exits of boolean sub-expression to point to appropriate code blocks, e.g., THEN and ELSE branches.
- If boolean-typed expression must deliver a value, true and false exits are defined to point to code that loads the value.

EXAMPLE (ASSUMING SHORT-CIRCUITING)

\[
\text{IF } (a > 7) \lor (b = 5) \text{ THEN } x = 7 \text{ ELSE } y = 2;
\]
\[
\begin{align*}
t1 & := \text{addr } a \\
t2 & := *t1 \\
t3 & := \text{const 7} \\
\text{if } t2 > t3 & \text{ goto L1} \\
t4 & := \text{const 0} \\
goto & L4 \\
\text{L1: } & \\
t12 & := \text{addr } x \\
t13 & := \text{addr } y \\
\text{L2: } & \\
t4 & := \text{addr } b \\
t5 & := *t4 \\
t6 & := \text{const 5} \\
\text{if } t5 = t6 & \text{ goto L1} \\
t8 & := \text{const 0} \\
goto & L4 \\
\text{L3: } & \\
t7 & := \text{const 7} \\
&t8 := \text{addr } x \\
\text{L4: } & \\
t4 & := \text{addr } a \\
t5 & := \text{addr } b \\
t6 & := *t4 \\
t7 & := \text{const 5} \\
\text{if } t5 = t6 & \text{ goto L3} \\
t8 & := \text{const 0} \\
goto & L4 \\
\text{L5: } & \\
t9 & := \text{const 2} \\
\text{L6: } &
\end{align*}
\]
**CONDITIONAL STATEMENTS (SOMewhat NAIVE APPROACH)**

Use control flow representation for boolean-typed expressions; define labels on per-statement basis.

\[
S := \text{IF } B \text{ THEN } S_1 \text{ ELSE } S_2 \\
B.\text{true} = \text{newlabel}() \\
B.\text{false} = \text{newlabel}() \\
S.\text{code} = \\
\quad \text{let after} = \text{newlabel()} \\
\quad \text{in } B.\text{code} @ \\
\quad \quad [\text{gen}(B.\text{true},:,:,_)] @ S_1.\text{code} @ \\
\quad \quad [\text{gen}(\text{after},\text{goto},_:_)] @ B.\text{false} = \text{newlabel}() \\
\quad \quad [\text{gen}(\text{after},:,:,_)] \\
\]

Generates:

\[
\text{IF } B \text{ GOTO L1} \\
\text{GOTO L2} \\
L1: S_1 \\
\text{GOTO L3} \\
L2: S_2 \\
L3: \\
\]

**RELATIONAL EXPRESSIONS**

Inherit true and false label attributes.

Synthesize code to perform appropriate test and jump to appropriate label.

Code doesn't build a value, so no place attribute.

\[
B := E_1 \ '=<' \ E_2 \\
B.\text{code} = E_1.\text{code} @ E_2.\text{code} @ \\
\quad [\text{gen}(B.\text{true},\text{if},E_1.\text{place},E_2.\text{place}), \\
\quad \quad \text{gen}(B.\text{false},\text{goto},_:_)] \\
B := E_1 \ '>=' \ E_2 \\
B.\text{code} = E_1.\text{code} @ E_2.\text{code} @ \\
\quad [\text{gen}(B.\text{true},\text{if},E_1.\text{place},E_2.\text{place}), \\
\quad \quad \text{gen}(B.\text{false},\text{goto},_:_)] \\
\]

**SHORT-CIRCUITING BOOLEAN EXPRESSIONS**

Inherit true and false label attributes.

Pass them down to subexpressions, after suitable manipulation; synthesize code attribute.

Again, no place attribute.

\[
B := B_1 \text{ OR } B_2 \\
B_1.\text{true} = B.\text{true} \\
B_1.\text{false} = \text{newlabel}() \\
B_2.\text{true} = B.\text{true} \\
B_2.\text{false} = B.\text{false} \\
B.\text{code} = B_1.\text{code} @ \\
\quad [\text{gen}(B_1.\text{false},:,:,_)] @ B_2.\text{code} \\
B := B_1 \text{ AND } B_2 \\
B_1.\text{true} = \text{newlabel}() \\
B_1.\text{false} = B.\text{false} \\
B_2.\text{true} = B.\text{true} \\
B_2.\text{false} = B.\text{false} \\
B.\text{code} = B_1.\text{code} @ \\
\quad [\text{gen}(B_1.\text{true},:,:,_)] @ B_2.\text{code} \\
B := \text{NOT } B_1 \\
B_1.\text{true} = B.\text{false} \\
B_1.\text{false} = B.\text{true} \\
B.\text{code} = B_1.\text{code} \\
\]
CONVERSION FROM VALUE FORM

Boolean-typed identifiers (variables, true and false constants) must be “converted” to control-flow form when tested.

\[ B := V \]
\[
B.code = V.code @ \[
\text{[gen}(B.false,\text{if=},V.place,0), \text{gen}(B.true,\text{goto},\_\_)]
\]

(Assuming 0 = false, non-0 = true)

CONVERSION TO VALUE FORM

Similarly, must convert other way when a value is needed, generating code to build a value into a place.

\[ E := B \]
\[
E.true = \text{newlabel}() \quad E.false = \text{newlabel}() \quad E.place = \text{newtemp}() \quad E.code = \]
\[
\text{let after = newlabel() in B.code @} \[
\text{[gen}(B.true,:,\_,\_), \text{gen}(E.place,:=,1,\_), \text{gen}(after,\text{goto},\_\_)]
\]
\[
\text{[gen}(B.false,:,\_,\_), \text{gen}(E.place,:=,0,\_), \text{gen}(after,:,\_,\_)]
\]

CAPTURING RELATIONAL TEST OUTCOMES

Many processors implement conditional jumps in two parts:

- a comparison instruction sets internal condition codes
- a conditional branch instruction tests the condition codes to decide whether or not to branch

Some processors allow the condition codes to be used to drive instructions other than conditional branches, e.g., the X86 supports

- set instructions that place a 1 or 0 value directly in a register based on the condition codes
- cmov instructions that conditionally move data (or not) based on the condition codes

Either of these can be used to generate much more efficient code when the value form of a relational expression is needed. (To express these, we would need to expand our IR, of course.)

HANDLING LOOP EXITS

Same label-passing approach can be used to implement break or exit statements that can cause jumps out of loops. We simply add a .break inherited attribute to statements!

\[ S := \text{BREAK} \]
\[
S.code = \text{gen}(S.break,\text{goto},\_\_)
\]
\[ S := \text{LOOP S END} \]
\[
S.break = \text{newlabel}() \quad S.code = \]
\[
\text{let top = newlabel() in [gen}(top,:,\_,\_) @} \]
\[
\text{[gen}(S.code@) \[
\text{[gen}(top,\text{goto},\_\_), \text{gen}(S.break,:,\_,\_)]
\]
\]

Other loop statements (like WHILE) must define and pass a similar appropriate label to their child statement.

All other (non-loop) statement translations must pass the .break attribute through (unchanged) to their children!
IMPROVING JUMP GENERATION

- Code for each statement always ends by “falling through” to next statement.
- There is no information flow between code generation for statements.

```latex
S := S1 ';' S2
S.code = S1.code @ S2.code
```

This can lead to bad code, e.g.,

```latex
WHILE B1 DO (WHILE B2 DO S)
L1: IF B1 GOTO L2
    GOTO L3
L2: IF B2 GOTO L4
    GOTO L5 "jump to jump"
L4: S
    GOTO L2
L5: GOTO L1
L3:
```

We can eliminate problems like this during optimization, but it’s easy to avoid some of them in the first place.

IDEA: DEFER DEFINITION OF TARGET LABELS

- Give each statement an inherited attribute .next, which says where to transfer control after statement.
- Code generated for each statement guarantees either to transfer control to .next label or to “fall through.”

```latex
S := S1 ';' S2
S1.next = newlabel()
S2.next = S.next
S.code = S1.code @ [gen(S1.next,:,_,_)] @
    S2.code
```

```
S := WHILE B DO S1
    B.true = newlabel()
    B.false = S.next
    S1.next = newlabel()
    S.code = [gen(S1.next,:,_,_)] @
    B.code @
    [gen(B.true,:,_,_)] @
    S1.code @
    [gen(S1.next,goto,_,_)]
```

Deferred label definition (continued)

Now get better code, e.g.

```latex
WHILE B1 DO (WHILE B2 DO S)
```

now generates

```latex
L1: IF B1 GOTO L2
    GOTO L3
L2: IF B2 GOTO L4
    GOTO L1
L3: S
    GOTO L2
...
L?:
```

BACKPATCHING

Target label attributes (true, false, break, etc.) are inherited, so won’t work with one-pass bottom-up code generation, e.g. when generating code while doing bottom-up parsing.

Solution: Instead, keep lists of locations of gotos that need to be filled in (“backpatched”) when final target is known. These backpatch lists are synthesized attributes.
Example (to fill in): \((a > 7) \text{ OR } (b = 5)\)

1. \(t1 := \text{addr } a\)
2. \(t2 := *t1\)
3. \(t3 := \text{const } 7\)
4. if \(t2 > t3\) goto _____
5. goto _____

6. \(t4 := \text{addr } b\)
7. \(t5 := *t4\)
8. \(t6 := \text{const } 5\)
9. if \(t5 = t6\) goto _____
10. goto _____

At reduction for \(B := B1 \text{ OR } B2\)

- Backpatch \(B1.\text{false}\) list with address of first instruction in \(B2\).
- Merge \(B1.\text{true}\) and \(B2.\text{true}\) to form \(B.\text{true}\).
- Make \(B2.\text{false}\) into \(B.\text{false}\).

Example (to fill in):

\[
\text{IF } (a > 7) \text{ OR } (b = 5) \text{ THEN } x := 7 \text{ ELSE } y := 2;
\]

1. \(t1 := \text{addr } a\)
2. \(t2 := *t1\)
3. \(t3 := \text{const } 7\)
4. if \(t2 > t3\) goto _____
5. goto _____
6. \(t4 := \text{addr } b\)
7. \(t5 := *t4\)
8. \(t6 := \text{const } 5\)
9. if \(t5 = t6\) goto _____
10. goto _____
11. \(t7 := \text{const } 7\)
12. \(t8 := \text{addr } x\)
13. \(*t8 := t7\)
14. goto _18_
15. \(t9 := \text{const } 2\)
16. \(t10 := \text{addr } y\)
17. \(*t10 := t9\)
18. ...

CASE STATEMENTS

\[
\text{case } e \text{ of } \\
\begin{align*}
    v_1 & : s_1 \\
    v_2 & : s_2 \\
    \ldots \\
    v_n & : s_n \\
\text{else } & \ s \\
\end{align*}
\]

End

Good code generation for case statement depends on analysis of the values on the case labels \(v_i\).

Options include:

- List of conditional tests and jumps (linear search).
- Binary decision code (binary tree).
- Other search code (e.g., hash table).
- Jump table (constant time).
- Hybrid schemes.
Case Statements (continued)

Best option depends on range of values (min and max) and their “density,” i.e., what percentage of the values in the range are used as labels.

Jump tables work well for dense value sets (even if large), but waste lots of space for sparse sets. Linear search works well for small value sets.