Compilation Principle
编 译 原 理

第17讲：中间代码(2)

张献伟

xianweiz.github.io

DCS290, 5/13/2021

Review Questions (1)

- What are the main tasks of compilation backend?

  Intermediate code generation, optimizations, target code generation

- What is IR (specifically, the low-level IR)?

  Intermediate Representation. A machine- and language-independent version of the original source code.

- Why do we use IR?

  Clean separation of front- and back-end; easy to optimize and extend

- What is three-address code (TAC)?

  A type of IR, with at most three operands. (High-level assembly)

- TAC of x + y * z + 5?

  t_1 = y * z; t_2 = x + t_1; t_3 = t_2 + 5;

Review Questions (2)

- Possible ways to implement TAC?

  Quadruples: op arg1, arg2, result
  Triples: op arg1 arg2
  Indirect triples: op arg1 arg2

- What is Single Static Assignment?

  An IR that facilitates certain code optimization.
  Give variable different version name on every assignment.

- In code generation, how to layout variables in memory?

  Calculate the location using base address and type width.

- What is address alignment?

  Enforce addr(x) % sizeof(x.type) == 0, to respect the hardware constraints to avoid unexpected performance degradation.

Code Generation[代码生成]

- To generate three-address codes (TACs)
  - By now, we have
    - an AST, annotated with scope and type information
  - Do another round of tree traversal
    - Lay out variables in memory
    - Generate TAC for any subexpressions or substatements
    - Using the result, generate TAC for the overall expression
- We will use the syntax-directed formalisms to specify translation
  - Variable definitions [变量定义]
  - Assignment [赋值]
  - Array references [数组引用]
  - Boolean expressions [布尔表达式]
  - Control-flow statements [控制流语句]

Type Expressions[类型表达式]

- A **type expression** is either a basic type or is formed by applying an operator called a <u>*type constructor*</u> [类型构造符] to a type expression
  - Basic type: *integer*, *float*, *char*, *Boolean*, *void*
  - Array: *array(I, T)* is a type expression, if *T* is
    - int[3] <--> array(3, int)
    - int[2][3] <--> array(2, array(3, int))
  - Pointer: *pointer(T)* is a type expression, if *T* is
    - int *val <--> pointer(int)

P -> D
D -> T id; D_1 | ε
T -> B C | * T_1
B -> int | real
C -> [num]C_1 | ε

CodeGen: Variable Definitions

- Translating variable definitions
  - *enter(name, type, offset)*
    - Save the type and relative address in the symbol-table entry for the name

① P -> { $offset = 0$ } D
② D -> T id; { $enter(\ id.lexeme,\ T.type,\ offset\ );$
$offset = offset + T.width;$ } D_1
③ D -> ε
④ T -> B { $t = B.type;\ w = B.width;$ }
C { $T.type = C.type;\ T.width = C.width;$ }
⑤ T -> $*T_1$ { $T.type = pointer(\ T_1.type);\ T.width = 4;$ }
⑥ B -> int { $B.type = int;\ B.width = 4;$ }
⑦ B -> real { $B.type = real;\ B.width = 8;$ }
⑧ C -> ε { $C.type = t;\ C.width = w;$ }
⑨ C -> [num]C_1 { $C.type = array(\ num.val,\ C_1.type);$
$C.width = num.val * C_1.width;$ }

- Examples:
  - *real x; int i;*
  - *int[2][3];*
- *type, width*
  - Syn attributes
- *t, w*
  - Vars to pass type and width from B node to the node for *C* -> ε
- *offset*
  - The next relative address

Example

- Input: real x; int i;

① $P \rightarrow \{\ offset = 0\ \}\ D$

② $D \rightarrow T\ \text{id};\ \{\ enter(\ id.lexeme,\ T.type,\ offset\ );$
$offset = offset + T.width;\ \}\ D_1$

③ $D \rightarrow \varepsilon$

④ $T \rightarrow B\ \{\ t = B.type;\ w = B.width;\ \}$
$C\ \{\ T.type = C.type;\ T.width = C.width;\ \}$

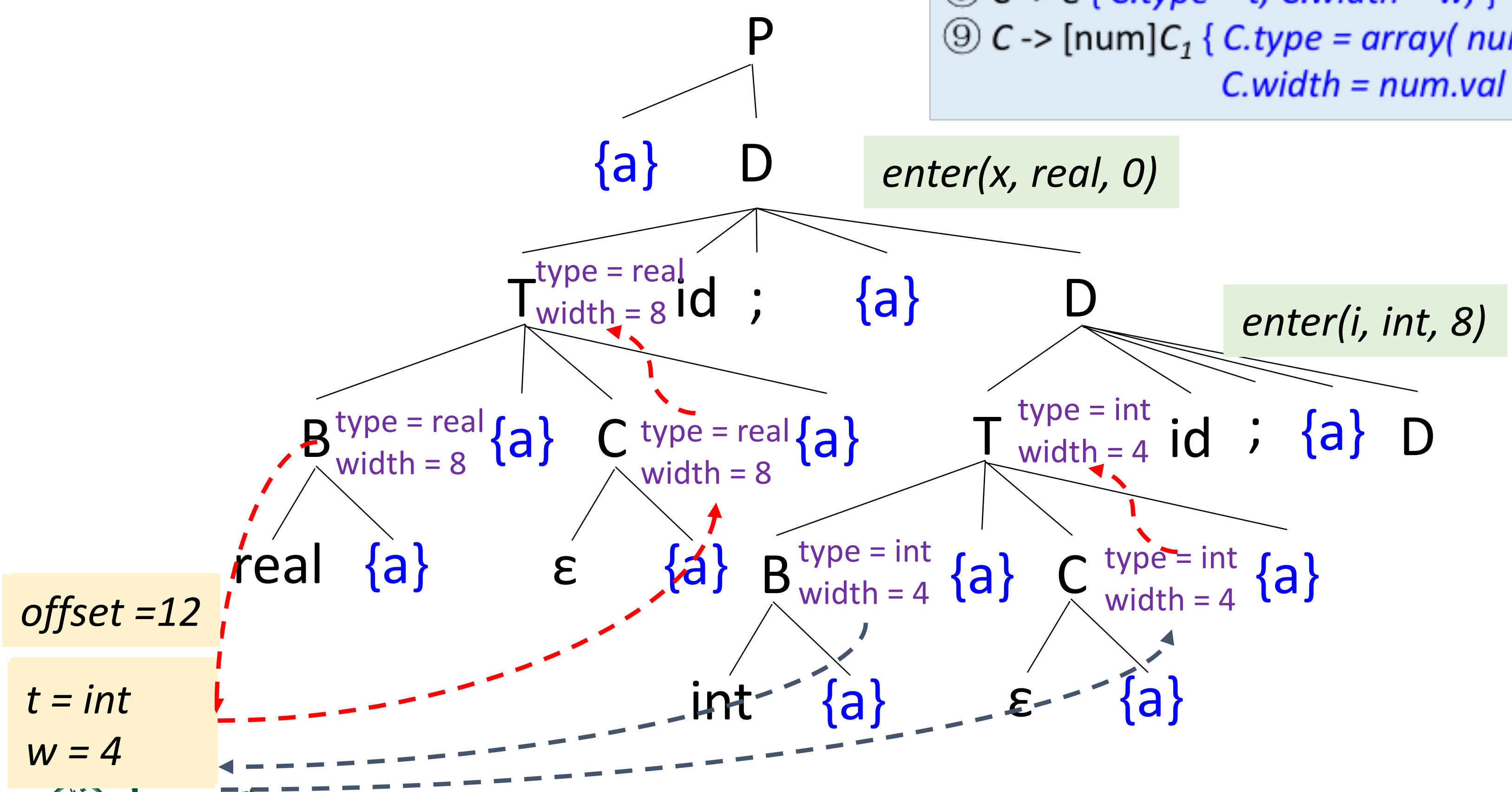
⑤ $T \rightarrow {}^{*}T_1\ \{\ T.type = pointer(\ T_1.type);\ T.width = 4;\ \}$

⑥ $B \rightarrow \text{int}\ \{\ B.type = int;\ B.width = 4;\ \}$

⑦ $B \rightarrow \text{real}\ \{\ B.type = real;\ B.width = 8;\ \}$

⑧ $C \rightarrow \varepsilon\ \{\ C.type = t;\ C.width = w;\ \}$

⑨ $C \rightarrow [\text{num}]C_1\ \{\ C.type = array(\ num.val,\ C_1.type);$
$C.width = num.val * C_1.width;\ \}$



CodeGen: Assignment Statement

- Translate into <u>*three-address code*</u> [赋值语句]
  - An expression with more than one operator will be translated into instructions with at most one operator per instruction
- Helper functions in translation
  - *lookup (id)*: search *id* in symbol table, return null if none
  - *emit()/gen()*: generate three-address IR
  - *newtemp()*: get a new temporary location

① S -> id = E;
② E -> E_1 + E_2;
③ E -> - E_1
④ E -> (E_1)
⑤ E -> id

Assignment statement:
a = b + (-c)

Three-address code:
t_1 = minus c
t_2 = b + t_1
a = t_2

SDT Translation of Assignment

- Attributes ***code*** and ***addr***
  - *S.code* and *E.code* denote the TAC for *S* and *E*, respectively
  - *E.addr* denotes the address that will hold the value of *E* (can be a name, constant, or a compiler-generated temporary)

① *S* -> id = *E*; { *p = lookup*(id.*lexeme); if !p then error;*
S.code = E.code ||
gen(p '=' E.addr); }

② *E* -> E_1 + E_2; { *E.addr = newtemp();*
E.code = E_1*.code ||* E_2*.code ||*
gen(E.addr '=' E_1*.addr '+'* E_2*.addr); }*

③ *E* -> - E_1 { *E.addr = newtemp();*
E.code = E_1*.code ||*
gen(E.addr '=' 'minus' E_1*.addr); }*

④ *E* -> (E_1) { *E.addr =* E_1*.addr;*
E.code = E_1*.code; }*

⑤ *E* -> id { *E.addr = lookup*(id.*lexeme); if !E.addr then error;*
E.code = ''; }

Incremental Translation[增量翻译]

- Generate only the new three-address instructions
  - *gen()* not only constructs a three-address inst, it appends the inst to the sequence of insts generated so far

① *S* -> id = *E*; { *p = lookup(*id.*lexeme); if !p then error;*

gen(p '=' E.addr); }

Code attributes can be long strings

② *E* -> E_1 + E_2; { *E.addr = newtemp();*

gen(E.addr '=' E_1.addr '+' E_2.addr); }

③ *E* -> - E_1 { *E.addr = newtemp();*

gen(E.addr '=' 'minus' E_1.addr); }

④ *E* -> (E_1) { *E.addr = E_1.addr;*

}

⑤ *E* -> id { *E.addr = lookup(*id.*lexeme); if !E.addr then error;*

}

Example

① S -> id = E; { p = lookup(id.lexeme); if !p then error;
gen(p '=' E.addr); }
② E -> E_1 + E_2; { E.addr = newtemp();
gen(E.addr '=' E_1.addr '+' E_2.addr); }
③ E -> - E_1 { E.addr = newtemp();
gen(E.addr '=' 'minus' E_1.addr); }
④ E -> (E_1) { E.addr = E_1.addr; }
⑤ E -> id { E.addr = lookup(id.lexeme); if !E.addr then error; }

- Input

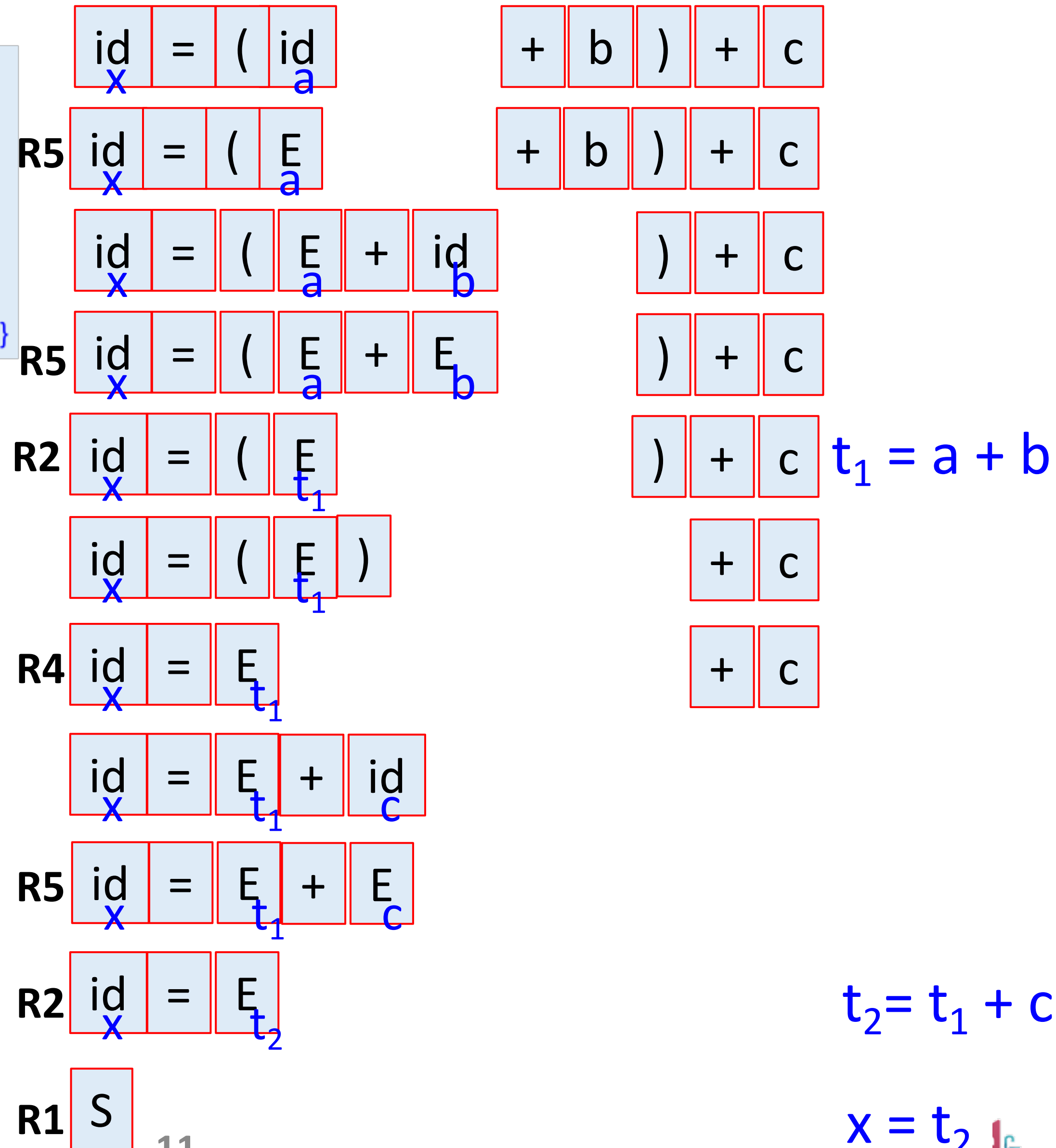
  $x = (a + b) + c$

- Translated TAC

  $t_1 = a + b$

  $t_2 = t_1 + c$

  $x = t_2$

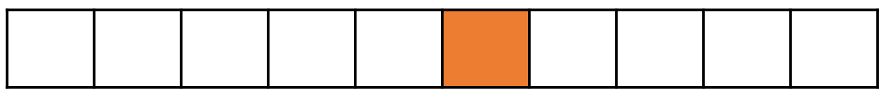


CodeGen: Array Reference[数组引用]

- Primary problem in generating code for array references is to *determine the address of element*
- 1D array

  int A[N];

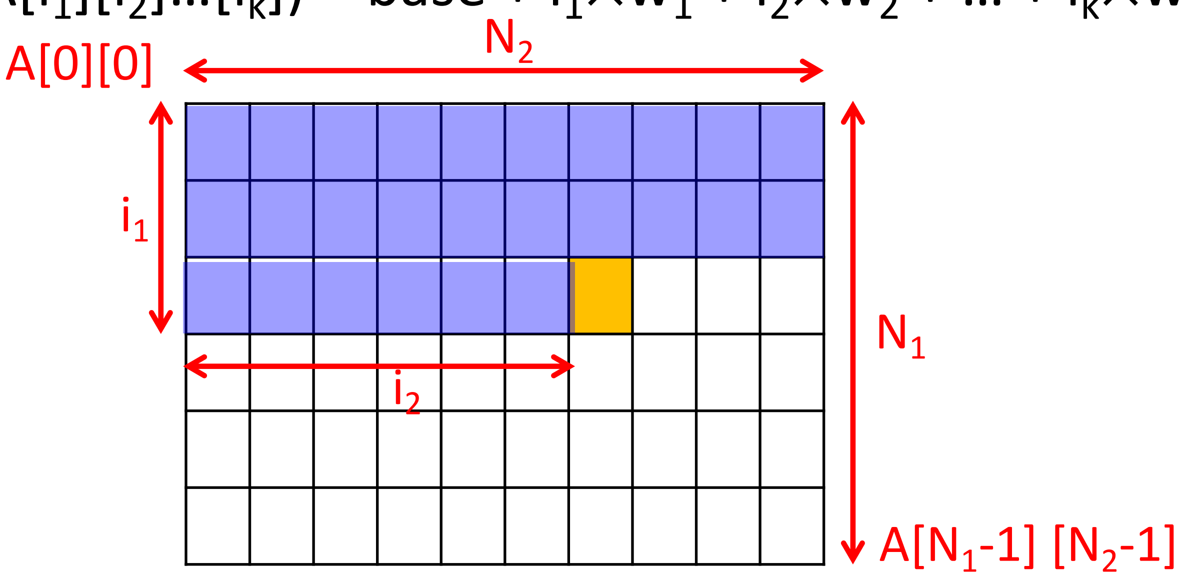
  A[i] ++;



  - *Base*: address of the first element
  - *Width*: width of each element
    - $i \times width$ is the offset
- Addressing an array element
  - addr(A[i]) = base + i×width

N-dimensional Array

- Laying out 2D array in 1D memory
  - *int A[N_1][N_2]; /* int A[0..N_1][0..N_2] */*
  - *A[i_1][i_2] ++;*
- The organization can be <u>row-major</u> or <u>column-major</u>
  - C language uses row major (i.e., stored row by row)
  - Row-major: $\text{addr}(A[i_1, i_2]) = \text{base} + (i_1 \times \underbrace{N_2 * \text{width}}_{w_1} + i_2 \times \underbrace{\text{width}}_{w_2})$
- *k*-dimensional array
  - $\text{addr}(A[i_1][i_2]...[i_k]) = \text{base} + i_1 \times w_1 + i_2 \times w_2 + ... + i_k \times w_k$



Translation of Array References

- Type(a) = array(10, int)
  - c = a[i];

addr(a[i]) = base + i*4

t_1 = i * 4
t_2 = a[t_1]
c = t_2

addr(a[i_1][i_2]) = base + i_1*20 + i_2*4

- Type(a) = array(3, array(5, int))
  - c = a[i_1][i_2];

t_1 = i_1 * 20
t_2 = i_2 * 4
t_3 = t_1 + t_2
t_4 = a[t_3]
c = t_4

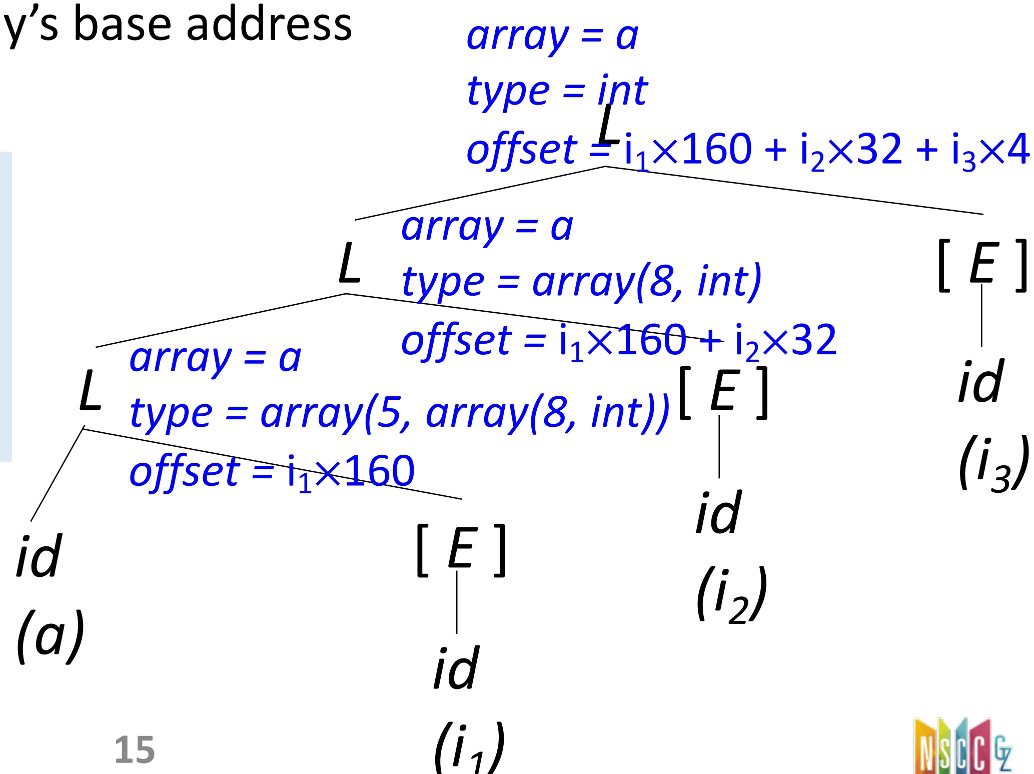
- Type(a) = array(3, array(5, array(8, int)))
  - c = a[i_1][i_2][i_3]

addr(a[i_1][i_2][i_3]) = base + i_1*w_1 + i_2*w_2 + i_3*w_3
= base + i_1*160 + i_2*32 + i_3*4

Translation of Array References (cont.)

- A$[i_1][i_2][i_3]$, type(a) = array(3, array(5, array(8, int)))
  - *L.type*: the type of the subarray generated by *L*
  - *L.addr*: a temporary that is used while computing the offset for the array reference by summing the terms $i_j \times w_j$
  - *L.array*: a pointer to the symbol-table entry for the array name
    - *L.array.base* gives the array's base address

① S -> id = E; | $L = E$;
② E -> $E_1 + E_2$ | - E_1 | (E_1) | id | L
③ L -> id [E] | L_1 [E]
$base + i_1 \times w_1 + i_2 \times w_2 + \ldots + i_k \times w_k$



Translation of Array References (cont.)

- $A[i_1][i_2][i_3]$, type(a) = array(3, array(5, array(8, int)))

① *S* -> id = *E*; | *L = E*; { *gen(L.array.base'['L.addr']' '=' E.addr);* }
② *E* -> E_1 + E_2 | - E_1 | (E_1) | id | *L* { *E.addr = newtemp();*
gen(E.addr '=' L.array.base'['L.addr']'); }
③ *L* -> id [*E*] { *L.array = lookup(id.lexeme); if !L.array then error;*
L.type = L.array.type.elem;
L.offset = newtemp();
gen(L.addr '=' E.addr '' L.type.width); }*
| L_1 [*E*] { *L.array* = L_1*.array;*
L.type = L_1*.type.elem;*
t = newtemp();
gen(t '=' E.addr '' L.type.width);*
L.addr = newtemp();
gen(L.addr '=' L_1*.addr '+' t; }*

$t_1 = i_1 * 160$
$t_2 = i_2 * 32$
$t_3 = t_1 + t_2$
$t_4 = i_3 * 4$
$t_5 = t_3 + t_4$
$c = a[t_5]$

CodeGen: Boolean Expressions

- Boolean expression: a *op* b
  - where op can be <, <=, = !=, > or >=, &&, ||, …
- **Short-circuit** evaluation[短路计算]: to skip evaluation of the rest of a boolean expression once a boolean value is known
  - Given following C code: *if (flag || foo()) { bar(); };*
    - If *flag* is true, *foo()* never executes
    - Equivalent to: *if (flag) { bar(); } else if (foo()) { bar(); };*
  - Given following C code: *if (flag && foo()) { bar(); };*
    - If *flag* is false, *foo()* never executes
    - Equivalent to: *if (!flag) { } else if (foo()) { bar(); };*
  - Used to alter control flow, or compute logical values
    - Examples: *if (x < 5) x = 1*; *x = true*; *x = a < b*
    - For control flow, boolean operators translate to ***jump*** statements

Boolean Exprs (w/o Short-Circuiting)

- Computed just like any other arithmetic expression

E -> (a < b) or (c < d and e < f)

t_1 = a < b
t_2 = c < d
t_3 = e < f
t_4 = t_2 && t_3
t_5 = t_1 || t_4

- Then, used in control-flow statements
  - *S.next*: label for code generated after *S*

S -> if E S1

if (!t_5) goto *S.next*
S_1.code
S.next: ...