Intermediate Code Generation

Cosmin E. Oancea
cosmin.oancea@diku.dk

Modified by Marco Valtorta for CSCE 531 at UofSC
Based on Jost Berthold's slides and Torben Mogensen's book
Department of Computer Science
University of Copenhagen

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Structure of a Compiler

Program text

↓

[Lexical analysis]

↓

Symbol sequence

↓

[Syntax analysis]

↓

Syntax tree

↓

[Typecheck]

↓

Syntax tree

↓

[Intermediate code generation] ⟶ Intermediate code

↑

[Machine code generation]

↑

Symbolic machine code

↑

[Register allocation]

↑

Ditto with named registers

↑

[Assembly and linking]

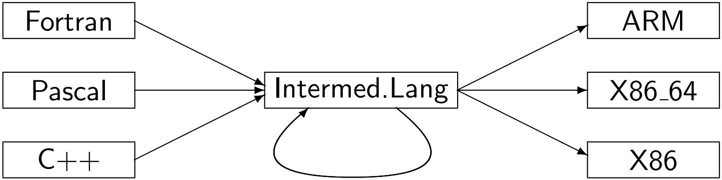
↑

Binary machine code

1. Why Intermediate Code?
   - Intermediate Language
   - To-Be-Translated Language
2. Syntax-Directed Translation
   - Arithmetic Expressions
   - Statements
   - Boolean Expressions, Sequential Evaluation
3. Translating More Complex Structures
   - More Control Structures
   - Arrays and Other Structured Data
   - Role of Declarations in the Translation

Why Intermediate Language (IL)?

- Compilers for different platforms and languages can share parts.



- Without IL: how many translators do I need to write to map `n` languages to `m` different hardware?

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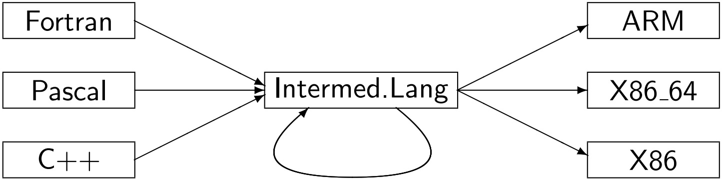

- Without IL: how many translators do I need to write to map `n` languages to `m` different hardware?
  Answer: `n*m` instead of `n+m`!

- Machine-independent optimizations are possible.

- Also enables interpretation ...

Intermediate Language (IL)

- Machine Independent: unlimited number of registers and memory space, no machine-specific instructions.

- Mid-level(s) between source and machine languages (tradeoff): simpler constructs, easier to generate machine code.

- What features/constructs should IL support?
  - every translation loses information $\Rightarrow$ use the information before losing it!
  - typically a chain of ILs moving from higher towards lower level.

- How complex should IL's instruction be?
  - complex: good for interpretation (amortizes instruction-decoding overhead),
  - simple: can more easily generate optimal machine code.

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Here: Low-level language, but keeping functions (procedures).
Small instructions:

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- Memory read/write (`M`) (address is atom).
- Jump labels, `GOTO` and conditional jump (`IF`).
- Function calls and returns

$$
\begin{array}{lcl}
Prg & \rightarrow & Fcts \\
Fcts & \rightarrow & Fct\ Fcts \mid Fct \\
Fct & \rightarrow & Hdr\ Bd \\
Hdr & \rightarrow & \textbf{functionid}(Args) \\
Bd & \rightarrow & [\ Instrs\ ] \\
Instrs & \rightarrow & Instr\ ,\ Instrs \mid Instr \\
Instr & \rightarrow & \textbf{id} := Atom \mid \textbf{id} := \textbf{unop}\ Atom \\
 & & \mid \textbf{id} := \textbf{id}\ \textbf{binop}\ Atom \\
 & & \mid \textbf{id} := M[Atom] \mid M[Atom] := \textbf{id} \\
 & & \mid \texttt{LABEL}\ \textbf{label} \mid \texttt{GOTO}\ \textbf{label} \\
 & & \mid \texttt{IF}\ \textbf{id}\ \textbf{relop}\ Atom \\
 & & \qquad \texttt{THEN}\ \textbf{label}\ \texttt{ELSE}\ \textbf{label} \\
Atom & \rightarrow & \textbf{id} \mid \textbf{num}
\end{array}
$$

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Here: Low-level language, but keeping functions (procedures).
Small instructions:

- 3-address code: one operation per expression
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\mathit{Fct} & \rightarrow & \mathit{Hdr}\ \mathit{Bd} \\
\mathit{Hdr} & \rightarrow & \textbf{functionid}(\mathit{Args}) \\
\mathit{Bd} & \rightarrow & [\ \mathit{Instrs}\ ] \\
\mathit{Instrs} & \rightarrow & \mathit{Instr}\ ,\ \mathit{Instrs} \mid \mathit{Instr} \\
\mathit{Instr} & \rightarrow & \textbf{id} := \mathit{Atom} \mid \textbf{id} := \textbf{unop}\ \mathit{Atom} \\
 & & \mid \textbf{id} := \textbf{id}\ \textbf{binop}\ \mathit{Atom} \\
 & & \mid \textbf{id} := M[\mathit{Atom}] \mid M[\mathit{Atom}] := \textbf{id} \\
 & & \mid \texttt{LABEL}\ \textbf{label} \mid \texttt{GOTO}\ \textbf{label} \\
 & & \mid \texttt{IF}\ \textbf{id}\ \textbf{relop}\ \mathit{Atom} \\
 & & \quad\quad \texttt{THEN}\ \textbf{label}\ \texttt{ELSE}\ \textbf{label} \\
 & & \mid \textbf{id} := \texttt{CALL}\ \textbf{functionid}(\mathit{Args}) \\
 & & \mid \texttt{RETURN}\ \textbf{id} \\
\mathit{Atom} & \rightarrow & \textbf{id} \mid \textbf{num} \\
\mathit{Args} & \rightarrow & \textbf{id}\ ,\ \mathit{Args} \mid \textbf{id}
\end{array}
$$

The To-Be-Translated Language

We shall translate a simple procedural language:

- Arithmetic expressions and function calls, boolean expressions,
- conditional branching (`if`),
- two loops constructs (`while` and `repeat until`).

Syntax-directed translation:

- In practice we work on the abstract syntax tree ABSYN (but here we use a generic grammar notation),
- Implement each syntactic category via a translation function: Arithmetic expressions, Boolean expressions, Statements.
- Code for subtrees is generated independent of context, (i.e., context is a parameter to the translation function and/or a value returned by the translation function)

Translating Arithmetic Expressions

Expressions in Source Language

- Variables and number literals,
- unary and binary operations,
- function calls (with argument list).

$$\begin{array}{lcl} \mathit{Exp} & \rightarrow & \textbf{num} \mid \textbf{id} \\ & & \mid \textbf{unop}\ \mathit{Exp} \\ & & \mid \mathit{Exp}\ \textbf{binop}\ \mathit{Exp} \\ & & \mid \textbf{id}(\mathit{Exps}) \\ \mathit{Exps} & \rightarrow & \mathit{Exp} \mid \mathit{Exp}\ ,\ \mathit{Exps} \end{array}$$

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 & & \mid \textbf{id}(\mathit{Exps}) \\
\mathit{Exps} & \rightarrow & \mathit{Exp} \mid \mathit{Exp}\ ,\ \mathit{Exps}
\end{array}
$$

Translation function:

$Trans_{Exp}$ `:: (Exp, VTable, FTable, Location) -> [ICode]`

- Returns a list of intermediate code instructions `[ICode]` that ...
- ... upon execution, computes `Exp`'s result in variable `Location`.
- Case analysis on `Exp`'s abstract syntax tree AbSyn.

Symbol Tables and Helper Functions

Translation function:

$Trans_{Exp}$ `:: (Exp, VTable, FTable, Location) -> [ICode]`

Symbol Tables

vtable : maps a variable name in source lang to its corresponding (translation) IL variable name.

ftable : function names to function labels (for `call`)

Helper Functions

- lookup: retrieve entry from a symbol table
- getvalue: retrieve value of source language literal
- getname: retrieve name of source language variable/operation
- newvar: make new intermediate code variable
- newlabel: make new label (for jumps in intermediate code)
- trans_op: translates an operator name to the name in IL.

Generating Code for an Expression

$Trans_{Exp}$: `(Exp, VTable, FTable, Location) -> [ICode]`

$Trans_{Exp}\ (exp, vtable, ftable, place) =$ `case` exp `of`

num	$v = getvalue(\textbf{num})$ $[place := v]$
id	$x = lookup(vtable, getname(\textbf{id}))$ $[place := x]$
unop Exp_1	$place_1 = newvar()$ $code_1 = Trans_{Exp}(Exp_1, vtable, ftable, place_1)$ $op = \texttt{trans\_op}(getname(\textbf{unop}))$ $code_1 \ \texttt{++}\ [place := op\ place_1]$
Exp_1 **binop** Exp_2	$place_1 = newvar()$ $place_2 = newvar()$ $code_1 = Trans_{Exp}(Exp_1, vtable, ftable, place_1)$ $code_2 = Trans_{Exp}(Exp_2, vtable, ftable, place_2)$ $op = \texttt{trans\_op}(getname(\textbf{binop}))$ $code_1 \ \texttt{++}\ code_2 \ \texttt{++}\ [place := place_1\ op\ place_2]$

Generating Code for a Function Call

$Trans_{Exp}$ $(exp, vtable, ftable, place)$ = `case` exp `of`

$\mathbf{id}(Exps)$	$(code_1, [a_1, \ldots, a_n]) = Trans_{Exps}(Exps, vtable, ftable)$ $fname = lookup(ftable, getname(\mathbf{id}))$ $code_1$ ++ $[place :=$ `CALL` $fname(a_1, \ldots, a_n)]$

$Trans_{Exps}$ returns the code that evaluates the function's parameters, and the list of new-intermediate variables (that store the result).

$Trans_{Exps}$ `: (Exps, VTable, FTable) -> ([ICode], [Location])`
$Trans_{Exps}(exps, vtable, ftable)$ = `case` $exps$ `of`

Exp	$place = newvar()$ $code_1 = Trans_{Exp}(Exp, vtable, ftable, place)$ $(code_1, [place])$
Exp , $Exps$	$place = newvar()$ $code_1 = Trans_{Exp}(Exp, vtable, ftable, place)$ $(code_2, args) = Trans_{Exps}(Exps, vtable, ftable)$ $code_3 = code_1$ ++ $code_2$ $args_1 = place :: args$ $(code_3, args_1)$

Translation Example

Assume the following symbol tables:

- vtable $= [x \mapsto v0,\ y \mapsto v1,\ z \mapsto v2]$
- ftable $= [f \mapsto \_F\_1, \mathtt{+} \mapsto \ \mathtt{+}, \mathtt{-} \mapsto \ \mathtt{-}]$

Translation of `Exp` with place $= t0$:

- `Exp=x-3`

Translation Example

Assume the following symbol tables:

- vtable $= [x \mapsto v0,\ y \mapsto v1,\ z \mapsto v2]$
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Translation of `Exp` with place $= t0$:

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```
t1 := v0
t2 := 3
t0 := t1 - t2
```

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Translation of `Exp` with place $= t0$:

- `Exp=x-3`

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t1 := v0
t2 := 3
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- `Exp=3+f(x-y,z)`

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Translation of `Exp` with place $= t0$:

- `Exp=x-3`
  $$\begin{array}{l} \texttt{t1} := \texttt{v0} \\ \texttt{t2} := 3 \\ \texttt{t0} := \texttt{t1} - \texttt{t2} \end{array}$$
- `Exp=3+f(x-y,z)`
  $$\begin{array}{l} \quad\texttt{t1} := 3 \\ \qquad\quad \texttt{t4} := \texttt{v0} \\ \qquad\quad \texttt{t5} := \texttt{v1} \\ \qquad \texttt{t3} := \texttt{t4} - \texttt{t5} \\ \qquad \texttt{t6} := \texttt{v2} \\ \quad \texttt{t2} := \texttt{CALL \_F\_1}(\texttt{t3}, \texttt{t6}) \\ \texttt{t0} := \texttt{t1} + \texttt{t2} \end{array}$$

Translating Statements

Statements in Source Language

- Sequence of statements
- Assignment
- Conditional Branching
- Loops: `while` and `repeat` (simple conditions for now)

$$
\begin{array}{lcl}
\mathit{Stat} & \rightarrow & \mathit{Stat}\ ;\ \mathit{Stat} \\
 & & \mid\ \mathbf{id} := \mathit{Exp} \\
 & & \mid\ \texttt{if}\ \mathit{Cond}\ \texttt{then}\ \{\ \mathit{Stat}\ \} \\
 & & \mid\ \texttt{if}\ \mathit{Cond}\ \texttt{then}\ \{\ \mathit{Stat}\ \}\ \texttt{else}\ \{\ \mathit{Stat}\ \} \\
 & & \mid\ \texttt{while}\ \mathit{Cond}\ \texttt{do}\ \{\ \mathit{Stat}\ \} \\
 & & \mid\ \texttt{repeat}\ \{\ \mathit{Stat}\ \}\ \texttt{until}\ \mathit{Cond} \\
\mathit{Cond} & \rightarrow & \mathit{Exp}\ \mathbf{relop}\ \mathit{Exp}
\end{array}
$$

We assume relational operators translate directly (using `trans_op`).

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\end{array}
$$

We assume relational operators translate directly (using `trans_op`).

Translation function:

$\mathit{Trans}_{\mathit{Stat}}$ `:: (Stat, VTable, FTable) -> [ICode]`

- As before: syntax-directed, case analysis on `Stat`
- Intermediate code instructions for statements

Generating Code for Sequences, Assignments,...

$Trans_{Stat}$ `: (Stat, Vtable, Ftable) -> [ICode]`

$Trans_{Stat}(stat, vtable, ftable) =$ `case` $stat$ `of`

$Stat_1$; $Stat_2$	$code_1 = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat_2, vtable, ftable)$ $code_1$ ++ $code_2$
$\mathbf{id} := Exp$	$place = lookup(vtable, getname(\mathbf{id}))$ $Trans_{Exp}(Exp, vtable, ftable, place)$
...	(rest coming soon)

- Sequence of statements, sequence of code.
- Symbol tables are inherited attributes.

Generating Code for Conditional Jumps: Helper

- Helper function for loops and branches
- Evaluates `Cond`, i.e., a boolean expression, then jumps to one of two labels, depending on result

$Trans_{Cond}$: `(Cond, Label, Label, Vtable, Ftable) -> [ICode]`
$Trans_{Cond}(cond, label_t, label_f, vtable, ftable) =$ `case` $cond$ `of`

Exp_1 **relop** Exp_2	$t_1 = newvar()$ $t_2 = newvar()$ $code_1 = Trans_{Exp}(Exp_1, vtable, ftable, t_1)$ $code_2 = Trans_{Exp}(Exp_2, vtable, ftable, t_2)$ $op = \texttt{trans\_op}(getname(\textbf{relop}))$ $code_1$ ++ $code_2$ ++ [`IF` t_1 op t_2 `THEN` $label_t$ `ELSE` $label_f$]

- Uses the `IF` of the intermediate language
- Expressions need to be evaluated before (restricted `IF`: only variables and atoms can be used)

Generating Code for If-Statements

- Generate new labels for branches and following code
- Translate `If` statement to a conditional jump

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$Trans_{Stat}(stat, vtable, ftable) =$ case $stat$ of	
if $Cond$ then $Stat_1$	$label_t = newlabel()$ $label_f = newlabel()$ $code_c = Trans_{Cond}(Cond, label_t, label_f, vtable, ftable)$ $code_s = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_c$ ++ [LABEL $label_t$] ++ $code_s$ ++ [LABEL $label_f$]
if $Cond$ then $Stat_1$ else $Stat_2$	$label_t = newlabel()$ $label_f = newlabel()$ $label_e = newlabel()$ $code_c = Trans_{Cond}(Cond, label_t, label_f, vtable, ftable)$ $code_1 = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat_2, vtable, ftable)$ $code_c$ ++ [LABEL $label_t$] ++ $code_1$ ++ [GOTO $label_e$] ++ [LABEL $label_f$] ++ $code_2$ ++ [LABEL $label_e$]

Generating Code for Loops

- `repeat-until` loop is the easy case:
  Execute body, check condition, jump back if false.
- `while` loop needs check before body, one extra label needed.

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$Trans_{Stat}(stat, vtable, ftable) =$ `case` $stat$ `of`

`repeat` $Stat$ `until` $Cond$	$label_f = newlabel()$ $label_t = newlabel()$ $code_1 = Trans_{Stat}(Stat, vtable, ftable)$ $code_2 = Trans_{Cond}(Cond, label_t, label_f, vtable, ftable)$ [LABEL $label_f$] ++ $code_1$ ++ $code_2$ ++ [LABEL $label_t$]
`while` $Cond$ `do` $Stat$	$label_s = newlabel()$ $label_t = newlabel()$ $label_f = newlabel()$ $code_1 = Trans_{Cond}(Cond, label_t, label_f, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat, vtable, ftable)$ [LABEL $label_s$] ++ $code_1$ ++ [LABEL $label_t$] ++ $code_2$ ++ [GOTO $label_s$] ++ [LABEL $label_f$]

Translation Example

- Symbol table vtable: $[x \mapsto v_0,\ y \mapsto v_1,\ z \mapsto v_2]$
- Symbol table ftable: [getInt $\mapsto$ libIO_getInt]

```
x := 3;
y := getInt();
z := 1;
while y > 0
    y := y - 1;
    z := z * x
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```
v_0 := 3
v_1 := CALL libIO_getInt()
v_2 := 1
```

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```
v_0 := 3
v_1 := CALL libIO_getInt()
v_2 := 1
 LABEL l_s
  t_1 := v_1
  t_2 := 0
  IF t_1 > t_2 THEN l_t else l_f
  LABEL l_t




  GOTO l_s
 LABEL l_f
```

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   t_3 := v_1
   t_4 := 1
   v_1 := t_3 - t_4




  GOTO l_s
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  t_1 := v_1
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  LABEL l_t
   t_3 := v_1
   t_4 := 1
   v_1 := t_3 - t_4
   t_5 := v_2
   t_6 := v_0
   v_2 := t_5 * t_6
  GOTO l_s
 LABEL l_f
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More Complex Conditions, Boolean Expressions

Boolean Expressions as Conditions

- Arithmetic expressions used as Boolean
- Logical operators (not, and, or)
- Boolean expressions used in arithmetics

$$
\begin{array}{lcl}
\mathit{Cond} & \rightarrow & \mathit{Exp}\ \textbf{relop}\ \mathit{Exp} \\
 & & \mid \mathit{Exp} \\
 & & \mid \textbf{not}\ \mathit{Cond} \\
 & & \mid \mathit{Cond}\ \textbf{and}\ \mathit{Cond} \\
 & & \mid \mathit{Cond}\ \textbf{or}\ \mathit{Cond} \\
\mathit{Exp} & \rightarrow & \ldots \mid \mathit{Cond}
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\end{array}
$$

We extend the translation functions $\mathit{Trans}_{\mathit{Exp}}$ and $\mathit{Trans}_{\mathit{Cond}}$:

- Interpret numeric values as Boolean expressions: 0 is **false**, all other values **true**.
- Likewise: truth values as arithmetic expressions

Numbers and Boolean Values, Negation

Expressions as Boolean values, negation:

$Trans_{Cond}$ `: (Cond, Label, Label, Vtable, Ftable) -> [ICode]`
$Trans_{Cond}(cond, label_t, label_f, vtable, ftable) =$ `case` $cond$ `of`

...	
Exp	$t = newvar()$ $code = Trans_{Exp}(Exp, vtable, ftable, t)$ $code$ ++ $[\texttt{IF } t \neq 0 \texttt{ THEN } label_t \texttt{ ELSE } label_f]$
not $Cond$	$Trans_{Cond}(Cond, label_f, label_t, vtable, ftable)$
...	

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...

Conversion of Boolean values to numbers (by jumps):

$Trans_{Exp}$: `(Exp, Vtable, Ftable) -> [ICode]`
$Trans_{Exp}(exp, vtable, ftable, place) =$ `case` exp `of`

...

$Cond$	$label_1 = newlabel()$ $label_2 = newlabel()$ $t = newvar()$ $code = Trans_{Cond}(Cond, label_1, label_2, vtable, ftable)$ $[t := 0]$ ++ $code$ ++ $[\texttt{LABEL}\ label_1,\ t := 1]$ ++ $[\texttt{LABEL}\ label_2,\ place := t]$

Sequential Evaluation of Conditions

```
Moscow ML version 2.01 (January 2004)
Enter `quit();' to quit.
- fun f l = if (hd l = 1) then "one" else "not one";
> val f = fn : int list -> string
- f [];
! Uncaught exception:
! Empty
```

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```

In most languages, logical operators are evaluated sequentially.

- If $B_1 = \mathit{false}$, do not evaluate B_2 in $B_1 \&\& B_2$ (anyway *false*).
- If $B_1 = \mathit{true}$, do not evaluate B_2 in $B_1 || B_2$ (anyway *true*).

Sequential Evaluation of Conditions

```
Moscow ML version 2.01 (January 2004)
Enter `quit();' to quit.
- fun f l = if (hd l = 1) then "one" else "not one";
> val f = fn : int list -> string
- f [];
! Uncaught exception:
! Empty
```

In most languages, logical operators are evaluated sequentially.

- If $B_1 = \mathit{false}$, do not evaluate B_2 in $B_1 \&\& B_2$ (anyway *false*).
- If $B_1 = \mathit{true}$, do not evaluate B_2 in $B_1 || B_2$ (anyway *true*).

```
- fun g l = if not (null l) andalso (hd l = 1) then "one" else "not one";
> val g = fn : int list -> string
- g [];
> val it = "not one" : string
```

Sequential Evaluation by “Jumping Code”

$Trans_{Cond}$ `: (Cond, Label, Label, Vtable, Ftable) -> [ICode]`

$Trans_{Cond}(cond, label_t, label_f, vtable, ftable) =$ `case` $cond$ `of`

...

$Cond_1$ **and** $Cond_2$	$label_{next} = newlabel()$ $code_1 = Trans_{Cond}(Cond_1, label_{next}, label_f, vtable, ftable)$ $code_2 = Trans_{Cond}(Cond_2, label_t, label_f, vtable, ftable)$ $code_1$ `++ [LABEL` $label_{next}$`] ++` $code_2$
$Cond_1$ **or** $Cond_2$	$label_{next} = newlabel()$ $code_1 = Trans_{Cond}(Cond_1, label_t, label_{next}, vtable, ftable)$ $code_2 = Trans_{Cond}(Cond_2, label_t, label_f, vtable, ftable)$ $code_1$ `++ [LABEL` $label_{next}$`] ++` $code_2$

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- Note: No logical operations in intermediate language! Logics of **and** and **or** encoded by jumps.

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- Alternative: Logical operators in intermediate language
  $$Cond \Rightarrow Exp \Rightarrow Exp \textbf{ binop } Exp$$
  Translated as an arithmetic operation.

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- Alternative: Logical operators in intermediate language

  $$Cond \Rightarrow Exp \Rightarrow Exp \ \textbf{binop} \ Exp$$

  Translated as an arithmetic operation. Evaluates both sides!

1. Why Intermediate Code?
   - Intermediate Language
   - To-Be-Translated Language
2. Syntax-Directed Translation
   - Arithmetic Expressions
   - Statements
   - Boolean Expressions, Sequential Evaluation
3. Translating More Complex Structures
   - More Control Structures
   - Arrays and Other Structured Data
   - Role of Declarations in the Translation

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- Case/Switch:
  $$\begin{array}{lcl} \mathit{Stat} & \rightarrow & \textbf{case}\ \mathit{Exp}\ \textbf{of}\ [\ \mathit{Alts}\ ] \\ \mathit{Alts} & \rightarrow & \textbf{num} : \mathit{Stat} \mid \textbf{num} : \mathit{Stat},\ \mathit{Alts} \end{array}$$
  When exited after each case: chain of `if-then-else`
  When "falling through" (e.g., in C): `if-then-else` and `goto`.

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- Break and Continue: $\mathit{Stat} \;\rightarrow\; \textbf{break} \mid \textbf{continue}$

  (`break`: jump behind loop, `continue`: jump to end of loop body).
  Needs two jump target labels used only inside loop bodies
  (parameters to translation function $\mathit{Trans}_{\mathit{Stat}}$)

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  ... considered harmful (Dijkstra 1968)

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  Needs to build symbol table of labels.
- Case/Switch: $\mathit{Stat} \rightarrow$ **case** *Exp* **of** [*Alts*]
  $\mathit{Alts} \rightarrow$ **num** : *Stat* | **num** : *Stat*, *Alts*

  When exited after each case: chain of `if-then-else`
  When "falling through" (e.g., in C): `if-then-else` and `goto`.
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Translating Arrays (of `int` elements)

Extending the Source Language

- Array elements used as an expression
- Assignment to an array element
- Array elements accessed by an index (expression)

$$
\begin{array}{lcl}
\mathit{Exp} & \rightarrow & \ldots \mid \mathit{Idx} \\
\mathit{Stat} & \rightarrow & \ldots \mid \mathit{Idx} \ := \ \mathit{Exp} \\
\mathit{Idx} & \rightarrow & \mathbf{id}[\ \mathit{Exp}\ ]
\end{array}
$$

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Stat & \rightarrow & \ldots \mid Idx \ := \ Exp \\
Idx & \rightarrow & \mathbf{id}[\ Exp\ ]
\end{array}
$$

Again we extend $Trans_{Exp}$ and $Trans_{Stat}$.

- Arrays stored in pre-allocated memory area, generated code will use memory access instructions.
- Static (compile-time) or dynamic (run-time) allocation possible.

Generating Code for Address Calculation

- *vtable* contains the base address of the array.
- Elements are `int` here, so 4 bytes per element for address.

$$
\begin{array}{ll}
\multicolumn{2}{l}{Trans_{Idx}(index, vtable, ftable) = \texttt{case}\ index\ \texttt{of}} \\
\hline
\textbf{id}[Exp] & base = lookup(vtable, getname(\textbf{id})) \\
 & addr = newvar() \\
 & code_1 = Trans_{Exp}(Exp, vtable, ftable, addr) \\
 & code_2 = code_1 \ +\!\!+ \ [addr := addr*4, addr := addr+base] \\
 & (code_2, addr) \\
\hline
\end{array}
$$

Returns:

- Code to calculate the absolute address ...
- of the array element in memory (corresponding to `index`), ...
- ...and a new variable (*addr*) where it will be stored.

Generating Code for Array Access

Address-calculation code: in expression and statement translation.

- Read access inside expressions:

$Trans_{Exp}(exp, vtable, ftable, place) = \texttt{case}\ exp\ \texttt{of}$

$\dots$

Idx	$(code_1, address) = Trans_{Idx}(Idx, vtable, ftable)$ $code_1 \texttt{ ++ } [place := M[address]]$

- Write access in assignments:

$Trans_{Stat}(stat, vtable, ftable) = \texttt{case}\ stat\ \texttt{of}$

$\dots$

$Idx := Exp$	$(code_1, address) = Trans_{Idx}(Index, vtable, ftable)$ $t = newvar()$ $code_2 = Trans_{Exp}(Exp, vtable, ftable, t)$ $code_1 \texttt{ ++ } code_2 \texttt{ ++ } [M[address] := t]$

Multi-Dimensional Arrays

Arrays in Multiple Dimensions

- Only a small change to previous grammar: *Idx* can now be recursive.
- Needs to be mapped to an address in one dimension.

$$
\begin{array}{lcl}
\mathit{Exp} & \rightarrow & \ldots \mid \mathit{Idx} \\
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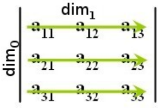
\mathit{Exp} & \to & \ldots \mid \mathit{Idx} \\
\mathit{Stat} & \to & \ldots \mid \mathit{Idx} \;:=\; \mathit{Exp} \\
\mathit{Idx} & \to & \mathbf{id}[\mathit{Exp}] \;\mid \mathit{Idx}[\mathit{Exp}]
\end{array}
$$

- Arrays stored in row-major or column-major order. Standard: row-major, index of `a[k][l]` is $k \cdot dim_1 + l$ (Index of `b[k][l][m]` is $k \cdot dim_1 \cdot dim_2 + l \cdot dim_2 + m$)



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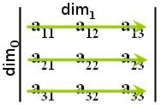

- Address calculation need to know sizes in each dimension.
  Symbol table: base address and list of array-dimension sizes.
- Need to change $Trans_{Idx}$, i.e., add recursive index calculation.

Address Calculation in Multiple Dimensions

$$
\begin{array}{l}
\mathit{Trans}_{\mathit{Idx}}(\mathit{index}, \mathit{vtable}, \mathit{ftable}) = \\
\hline
\qquad (\mathit{code}_1, t, \mathit{base}, []) = \mathit{Calc}_{\mathit{Idx}}(\mathit{index}, \mathit{vtable}, \mathit{ftable}) \\
\qquad \mathit{code}_2 = \mathit{code}_1 \text{ ++ } [t := t * 4, t := t + \mathit{base}] \\
\qquad (\mathit{code}_2, t) \\
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Address Calculation in Multiple Dimensions

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Trans_{Idx}(index, vtable, ftable) = \\
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\quad (code_2, t) \\
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$$

Recursive index calculation, multiplies with dimension at each step.

$$
\begin{array}{ll}
\multicolumn{2}{l}{Calc_{Idx}(index, vtable, ftable) = \texttt{case}\ index\ \texttt{of}} \\
\hline
\mathbf{id}[Exp] & (base, dims) = lookup(vtable, getname(\mathbf{id})) \\
 & addr = newvar() \\
 & code = Trans_{Exp}(Exp, vtable, ftable, addr) \\
 & (code, addr, base, tail(dims)) \\
\hline
Index[Exp] & (code_1, addr, base, dims) = Calc_{Idx}(Index, vtable, ftable) \\
 & d = head(dims) \\
 & t = newvar() \\
 & code_2 = Trans_{Exp}(Exp, vtable, ftable, t) \\
 & code_3 = code_1 \;\; ++ \;\; code_2 \;\; ++ \;\; [addr := addr * d, addr := addr + t] \\
 & (code_3, addr, base, tail(dims)) \\
\hline
\end{array}
$$

Declarations in the Translation

Declarations are necessary

- to allocate space for arrays,
- to compute addresses for multi-dimensional arrays,
- . . . and when the language allows local declarations (scope).

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Declarations and scope

- Statements following a declarations can see declared data.
- Declaration of variables and arrays
- Here: Constant size, one dimension

$$
\begin{array}{lcl}
\mathit{Stat} & \rightarrow & \mathit{Decl};\ \mathit{Stat} \\
\mathit{Decl} & \rightarrow & \texttt{int}\ \mathbf{id} \\
 & & \mid \texttt{int}\ \mathbf{id[num]}
\end{array}
$$

Function $\mathit{Trans}_{\mathit{Decl}}$ `: (Decl, VTable) -> ([ICode], VTable)`

- translates declarations to code and new symbol table.

Translating Declarations to Scope and Allocation

Code with local scope (extended symbol table):

$Trans_{Stat}(stat, vtable, ftable) = \texttt{case}\ stat\ \texttt{of}$	
$Decl\ ;\ Stat_1$	$(code_1, vtable_1) = Trans_{Decl}(Decl, vtable)$ $code_2 = Trans_{Stat}(Stat_1, vtable_1, ftable)$ $code_1\ \texttt{++}\ code_2$

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\hline
\end{array}$$

Building the symbol table and allocating:

$Trans_{Decl}$ `: (Decl, VTable) -> ([ICode], VTable )`

$$\begin{array}{ll}
\multicolumn{2}{l}{Trans_{Decl}(decl, vtable) = \texttt{case}\ decl\ \texttt{of}} \\
\hline
\texttt{int}\ \mathbf{id} & t_1 = newvar() \\
 & vtable_1 = bind(vtable, getname(\mathbf{id}), t_1) \\
 & ([],\ vtable_1) \\
\hline
\texttt{int}\ \mathbf{id}[\mathbf{num}] & t_1 = newvar() \\
 & vtable_1 = bind(vtable, getname(\mathbf{id}), t_1) \\
 & ([t_1 := HP,\ HP := HP + (4 * getvalue(\mathbf{num}))],\ vtable_1) \\
\hline
\end{array}$$

...where `HP` is the heap pointer, indicating the first free space in a managed heap at runtime; used for dynamic allocation.

Other Structures that Require Special Treatment

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  Often stored in different registers
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  Usually handled by library functions.
- Records and Unions
  Linear in memory. Field types and sizes can be different.
  Field selector known at compile time: compute offset from base.

Structure of a Compiler

Program text
↓
Lexical analysis
↓
Symbol sequence
↓
Syntax analysis
↓
Syntax tree
↓
Typecheck
↓
Syntax tree
↓
Intermediate code generation ⟶ Intermediate code
↑
Machine code generation
↑
Symbolic machine code
↑
Register allocation
↑
Ditto with named registers
↑
Assembly and linking
↑
Binary machine code