Faculty of Science

Intermediate Code Generation

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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

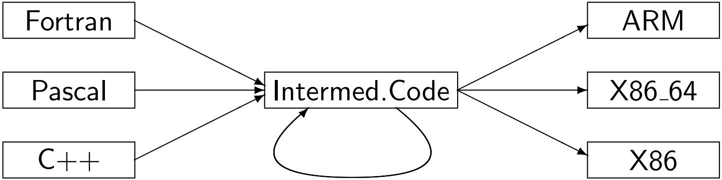
↑

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 Code?

- Compilers for different platforms and languages can share parts.



- Machine-independent optimizations are possible.

- Also enables interpretation ...

Intermediate Language (IL)

- Machine Independent: no limit on register and memory, 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;
  - use the information before losing it!

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

Intermediate Language (IL)

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

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- Memory read/write (`M`) (address is atom).
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- 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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 & & \mid \texttt{IF}\ \mathbf{id}\ \mathbf{relop}\ Atom \\
 & & \quad \texttt{THEN}\ \mathbf{label}\ \texttt{ELSE}\ \mathbf{label} \\
 & & \mid \mathbf{id} := \texttt{CALL}\ \mathbf{functionid}(Args) \\
 & & \mid \texttt{RETURN}\ \mathbf{id} \\
Atom & \rightarrow & \mathbf{id} \mid \mathbf{num} \\
Args & \rightarrow & \mathbf{id}\ ,\ Args \mid \mathbf{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)

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Translating Arithmetic Expressions

Expressions in Source Language

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

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

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

Translation function:

$\mathit{Trans}_{\mathit{Exp}}$ `:: (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 : variable names to intermediate code variables

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

Generating Code for a Function Call

$Trans_{Exp}$ $(exp, vtable, ftable, place)$ = case exp of	
$\mathbf{id}(Exps)$	$(code_1, [a_1, \ldots, a_n]) = Trans_{Exps}(Exps, vtable, ftable)$ $fname = lookup(ftable, getname(\mathbf{id}))$ $code_1$ @ $[place := \texttt{CALL}\ fname(a_1, \ldots, a_n)]$

$Trans_{Exps}$ 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 $= [f \mapsto \_F\_1]$

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

- `Exp=x-3`

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

- `Exp=x-3`

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

Translation Example

Assume the following symbol tables:

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

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

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

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

- `Exp=x-3`

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

- `Exp=3+f(x-y,z)`

```
t1 := 3
  t4 := v0
  t5 := v1
 t3 := t4 - t5
 t6 := v2
t2 := CALL _F_1(t3, t6)
t0 := t1 + t2
```

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Translating Statements

Statements in Source Language

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

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

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

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& & \mid\ \texttt{if}\ \mathit{Cond}\ \texttt{then}\ \{\ \mathit{Stat}\ \} \\
& & \mid\ \texttt{if}\ \mathit{Cond}\ \texttt{then}\ \{\ \mathit{Stat}\ \} \\
& & \qquad\qquad \texttt{else}\ \{\ \mathit{Stat}\ \} \\
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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`

$Stat_1\ ;\ Stat_2$	$code_1 = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat_2, vtable, ftable)$ $code_1$ @ $code_2$
$\textbf{id} := Exp$	$place = lookup(vtable, getname(\textbf{id}))$ $Trans_{Exp}(Exp, vtable, ftable, place)$

... (rest coming soon)

- Sequence of statements, sequence of code.
- Symbol tables are inherited attributes.
- When are associations added to `vtable` ?

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	$t_1 = newvar()$ $t_2 = newvar()$ $code_1 = Trans_{Exp}(Exp_1, vtable, ftable, t_1)$ $code_2 = Trans_{Exp}(Exp_2, vtable, ftable, t_2)$ $op =$ `trans_op`$(getname(\mathbf{relop}))$ $code_1$ @ $code_2$ @ [`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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$Trans_{Stat}(stat, vtable, ftable) = \texttt{case}\ stat\ \texttt{of}$

`if` $Cond$ `then` $Stat_1$	$label_t = newlabel()$ $label_f = newlabel()$ $code_1 = Trans_{Cond}(Cond, label_t, label_f, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_1$ @ [LABEL $label_t$] @ $code_2$ @ [LABEL $label_f$]
`if` $Cond$ `then` $Stat_1$ `else` $Stat_2$	$label_t = newlabel()$ $label_f = newlabel()$ $label_e = newlabel()$ $code_1 = Trans_{Cond}(Cond, label_t, label_f, vtable, ftable)$ $code_2 = Trans_{Stat}(Stat_1, vtable, ftable)$ $code_3 = Trans_{Stat}(Stat_2, vtable, ftable)$ $code_1$ @ [LABEL $label_t$] @ $code_2$ @ [GOTO $label_e$] @ [LABEL $label_f$] @ $code_3$ @ [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 ↦ libIO_getInt]

```
x := 3;
y := getInt();
z := 1;
while y > 0
    y := y - 1;
    z := z * x
```

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v0 := 3
v1 := CALL libIO_getInt()
v2 := 1
```

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

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while y > 0
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```

```
v0 := 3
v1 := CALL libIO_getInt()
v2 := 1
 LABEL ls
  t1 := v1
  t2 := 0
  IF t1 > t2 THEN lt else lf
  LABEL lt





  GOTO ls
 LABEL lf
```

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  IF t1 > t2 THEN lt else lf
  LABEL lt
   t3 := v1
   t4 := 1
   v1 := t3 - t4



  GOTO ls
 LABEL lf
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  t1 := v1
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  LABEL lt
   t3 := v1
   t4 := 1
   v1 := t3 - t4
   t5 := v2
   t6 := v0
   v2 := t5 * t6
  GOTO ls
 LABEL lf
```

More Complex Conditions, Boolean Expressions

Boolean Expressions as Conditions

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

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

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

We extend the translation functions $Trans_{Exp}$ and $Trans_{Cond}$:

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

...

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

...

Conversion of Boolean values to numbers (by jumps):

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

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

...

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

Paladim's And/If-Then-Else by "Jumping Code"

$Trans_{Cond}$ is inlined in the implementation of And/If-Then-Else

```
| compileExp( vtable, And(e1, e2, _), place ) =
    let val (t1, t2) = ("and1_"^newName(), "and2_"^newName() )
        val c1 = compileExp(vtable, e1, t1)
        val c2 = compileExp(vtable, e2, t2)
        val lA = "_and_" ^ newName()
    in c1 @ [Mips.MOVE (place,t1),  Mips.BEQ (place, "0", lA) ]
     @ c2 @ [Mips.MOVE (place,t2),  Mips.LABEL lA ]
    end
      ...
| compileStmt(vtable, s, exitLabel) = case s of ...
    | IfThEl (e,blockT,blockF,p) =>
        let val (ereg, els) = ("_if_" ^ newName(), "_else_" ^ newName())
            val endl  = "_endif_" ^ newName()
            val codeE = compileExp(vtable, e, ereg)
            val codeT = compileStmts blockT vtable exitLabel
            val codeF = compileStmts blockF vtable exitLabel
        in codeE @ [ Mips.BEQ (ereg, "0", els) ]
           @ codeT @ [ Mips.J endl]
           @ ( Mips.LABEL els) :: codeF @ [ Mips.LABEL endl ]
        end
```

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*).

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- 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 $label_{next}$] @ $code_2$
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- Case/Switch:
  $$\begin{array}{lcl} \mathit{Stat} & \rightarrow & \textbf{case}\ \mathit{Exp}\ \textbf{of}\ [\ \mathit{Alts}\ ] \\ \mathit{Alts} & \rightarrow & \textbf{num} : \mathit{Stat} \mid \textbf{num} : \mathit{Stat},\ \mathit{Alts} \end{array}$$
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- Break and Continue: $Stat \rightarrow$ **break** | **continue**
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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 & \textbf{id}[\ \mathit{Exp}\ ]
\end{array}
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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.

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

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:

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

$$\begin{array}{ll}
\quad \ldots & \\
\hline
Idx & (code_1, address) = Trans_{Idx}(Idx, vtable, ftable) \\
 & code_1 \texttt{ @ } [place := M[address]] \\
\hline
\end{array}$$

- Write access in assignments:

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

$$\begin{array}{ll}
\quad \ldots & \\
\hline
Idx := Exp & (code_1, address) = Trans_{Idx}(Index, vtable, ftable) \\
 & t = newvar() \\
 & code_2 = Trans_{Exp}(Exp, vtable, ftable, t) \\
 & code_1 \texttt{ @ } code_2 \texttt{ @ } [M[address] := t] \\
\hline
\end{array}$$

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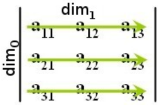
- Arrays stored in row-major or column-major order.
  Standard: row-major, index of `a[k][l]` is $k \cdot dim_1 + l$
  (Index of `b[k][l][m]` is $k \cdot dim_1 \cdot dim_2 + l \cdot dim_2 + m$)



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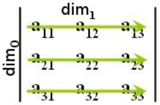

- Address calculation need to know sizes in each dimension.
  Symbol table: base address and list of array-dimension sizes.
- Need to change $Trans_{Idx}$, i.e., add recursive index calculation.

Address Calculation in Multiple Dimensions

$$\mathit{Trans}_{\mathit{Idx}}(\mathit{index}, \mathit{vtable}, \mathit{ftable}) =$$

$$\begin{array}{l} (\mathit{code}_1, t, \mathit{base}, []) = \mathit{Calc}_{\mathit{Idx}}(\mathit{index}, \mathit{vtable}, \mathit{ftable}) \\ \mathit{code}_2 = \mathit{code}_1 \texttt{ @ } [t := t * 4, t := t + \mathit{base}] \\ (\mathit{code}_2, t) \end{array}$$

Address Calculation in Multiple Dimensions

$$Trans_{Idx}(index, vtable, ftable) =$$

$$(code_1, t, base, []) = Calc_{Idx}(index, vtable, ftable)$$
$$code_2 = code_1 \; @ \; [t := t * 4, t := t + base]$$
$$(code_2, t)$$

Recursive index calculation, multiplies with dimension at each step.

$Calc_{Idx}(index, vtable, ftable) = \texttt{case}\ index\ \texttt{of}$

$\mathbf{id}[Exp]$	$(base, dims) = lookup(vtable, getname(\mathbf{id}))$ $addr = newvar()$ $code = Trans_{Exp}(Exp, vtable, ftable, addr)$ $(code, addr, base, tail(dims))$
$Index[Exp]$	$(code_1, addr, base, dims) = Calc_{Idx}(Index, vtable, ftable)$ $d = head(dims)$ $t = newvar()$ $code_2 = Trans_{Exp}(Exp, vtable, ftable, t)$ $code_3 = code_1 \; @ \; code_2 \; @ \; [addr := addr * d, addr := addr + t]$ $(code_3, addr, base, tail(dims))$

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

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

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):

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

Translating Declarations to Scope and Allocation

Code with local scope (extended symbol table):

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

$Decl\ ;\ Stat_1$	$(code_1, vtable_1) = Trans_{Decl}(Decl, vtable)$ $code_2 = Trans_{Stat}(Stat_1, vtable_1, ftable)$ $code_1$ `@` $code_2$

Building the symbol table and allocating:

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

$Trans_{Decl}(decl, vtable) =$ `case` $decl$ `of`

`int` **id**	$t_1 = newvar()$ $vtable_1 = bind(vtable, getname(\mathbf{id}), t_1)$ $([\,],\ vtable_1)$
`int` **id[num]**	$t_1 = newvar()$ $vtable_1 = bind(vtable, getname(\mathbf{id}), t_1)$ $([t_1 := HP,\ HP := HP + (4 * getvalue(\mathbf{num}))],\ vtable_1)$

...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

- Floating-Point values:
  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