Compilerconstructie

najaar 2012

http://www.liacs.nl/home/rvvliet/coco/

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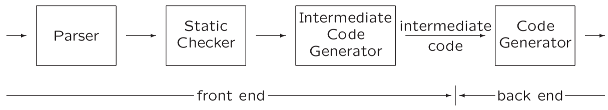
college 6, dinsdag 23 oktober 2012

Intermediate Code Generation

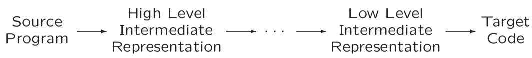
6. Intermediate Code Generation

- Front end: generates intermediate representation
- Back end: generates target code



Intermediate Representation

- Facilitates efficient compiler suites: $m+n$ instead of $m*n$
- Different types, e.g.,
  - syntax trees
  - three-address code: $x = y$ *op* z
- High-level vs. low-level
- C for C++

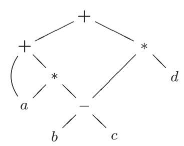


6.2 Three-Address Code

- Linearized representation of syntax tree / syntax DAG
- Sequence of instructions: $x = y$ *op* z

Example: $a + a*(b-c) + (b-c)*d$

Syntax DAG



Three-address code

```
t1 = b - c
t2 = a * t1
t3 = a * t2
t4 = t1 * d
t5 = t3 + t4
```


Addresses

At most three addresses per instruction

- Name: source program name / symbol-table entry
- Constant
- Compiler-generated temporary: distinct names

Three-Address Instructions

1	Assignment instructions	$x = y$ *op* z
2	Assignment instructions	$x =$ *op* y
3	Copy instructions	$x = y$
4	Unconditional jumps	goto L
5	Conditional jumps	if x goto L / ifFalse x goto L
6	Conditional jumps	if x *relop* y goto L / ifFalse...
7	Procedure calls and returns	param x_1 param x_2 ... param x_n call p, n return y
8	Indexed copy instructions	$x = y[i]$ / $x[i] = y$
9	Address and pointer assignments	$x = \&y$, $x = *y$, $*x = y$

Symbolic lable L represents index of instruction

Three-Address Instructions (Example)

```
do i = i+1; while (a[i] < v);
```

Syntax tree...

Two examples of possible translations:

Symbolic labels	Position numbers
`L: t1 = i+1`	`100: t1 = i+1`
`i = t1`	`101: i = t1`
`t2 = i * 8`	`102: t2 = i * 8`
`t3 = a [ t2 ]`	`103: t3 = a [ t2 ]`
`if t3 < v goto L`	`104: if t3 < v goto 100`

Implementation of Three-Address Instructions

Quadruples: records *op*, *vararg*1, *vararg*2, *result*

Example: `a = b * - c + b * - c`

Syntax tree...

Three-address code

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	op	*vararg*1	*vararg*2	*result*
0	minus	c		t_1
1	$*$	b	t_1	t_2
2	minus	c		t_3
3	$*$	b	t_3	t_4
4	$+$	t_2	t_4	t_5
5	$=$	t_5		a
		...		

Implementation of Three-Address Instructions

Three-address code

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	op	*varg1*	*varg2*	*result*
0	minus	c		t_1
1	$*$	b	t_1	t_2
2	minus	c		t_3
3	$*$	b	t_3	t_4
4	$+$	t_2	t_4	t_5
5	$=$	t_5		a
		...		

Exceptions

1. minus, $=$
2. param
3. jumps

Field *result* mainly for temporaries...

Implementation of Three-Address Instructions

Triples: records *op*, *varg1*, *varg2*

Example: `a = b * - c + b * - c`

Syntax tree...

Three-address code

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	op	*varg1*	*varg2*
0	minus	c	
1	$*$	b	(0)
2	minus	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	t_5
		...	

Implementation of Three-Address Instructions

Three-address code

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	op	*varg1*	*varg2*
0	minus	c	
1	$*$	b	(0)
2	minus	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	t_5
		...	

Equivalent to DAG

Special case: $x[i] = y$ or $x = y[i]$

Pro: temporaries are implicit
Con: difficult to rearrange code

Implementation of Three-Address Instructions

Indirect triples: pointers to triples

Example: `a = b * - c + b * - c`

Syntax tree...

Three-address code

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	instruction
35	(0)
36	(1)
37	(2)
38	(3)
39	(4)
40	(5)
	...

	op	*varg1*	*varg2*
0	minus	c	
1	$*$	b	(0)
2	minus	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	(4)
		...	

6.3.3 Declarations

- Three-address code is simplistic
  It assumes that names of variables can be easily resolved by the back end in global or local variables
- We need symbol tables to record global and local declarations in procedures, blocks, and structs to resolve names
- Symbol table contains type and relative adress of names

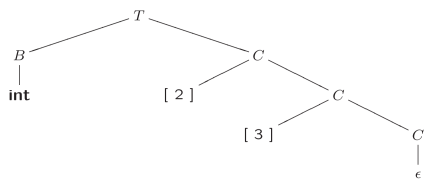
Example:

$$
\begin{array}{lcl}
D & \to & T\ \mathbf{id};D \mid \epsilon \\
T & \to & B\ C \mid \mathbf{record}\ '\{'\ D\ '\}' \\
B & \to & \mathbf{int} \mid \mathbf{float} \\
C & \to & \epsilon \mid [\ \mathbf{num}\ ]\ C
\end{array}
$$

Structure of Types (Example)

$$
\begin{array}{lcl}
T & \to & B\ C \mid \mathbf{record}\ '\{'\ D\ '\}' \\
B & \to & \mathbf{int} \mid \mathbf{float} \\
C & \to & \epsilon \mid [\ \mathbf{num}\ ]\ C
\end{array}
$$

`int[2][3]`



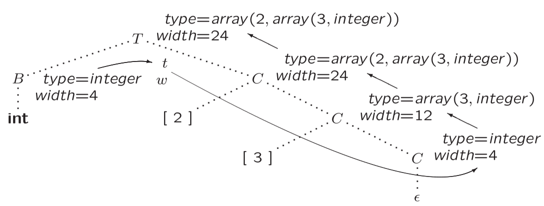
Storage Layout at Compile Time

- Storage comes in blocks of contiguous bytes
- Width of type is number of bytes needed

$$
\begin{array}{lcll}
T & \to & B & \{\ t = B.type;\ w = B.width;\ \} \\
 & & C & \{\ T.type = C.type;\ T.width = C.width;\ \} \\
B & \to & \mathbf{int} & \{\ B.type = integer;\ B.width = 4;\ \} \\
B & \to & \mathbf{float} & \{\ B.type = float;\ B.width = 8;\ \} \\
C & \to & \epsilon & \{\ C.type = t;\ C.width = w;\ \} \\
C & \to & [\ \mathbf{num}\ ]\ C_1 & \{\ C.type = array(\mathbf{num}.value,\ C_1.type); \\
 & & & \quad C.width = \mathbf{num}.value \times C_1.width;\ \}
\end{array}
$$

Types and Their Widths (Example)

$$
\begin{array}{lcll}
T & \to & B & \{\ t = B.type;\ w = B.width;\ \} \\
 & & C & \{\ T.type = C.type;\ T.width = C.width;\ \} \\
B & \to & \mathbf{int} & \{\ B.type = integer;\ B.width = 4;\ \} \\
B & \to & \mathbf{float} & \{\ B.type = float;\ B.width = 8;\ \} \\
C & \to & \epsilon & \{\ C.type = t;\ C.width = w;\ \} \\
C & \to & [\ \mathbf{num}\ ]\ C_1 & \{\ C.type = array(\mathbf{num}.value,\ C_1.type); \\
 & & & \quad C.width = \mathbf{num}.value \times C_1.width;\ \}
\end{array}
$$



Sequences of Declarations

$$D \rightarrow T\ \textbf{id};D \mid \epsilon$$

Use *offset* as next available address

$$
\begin{array}{lll}
P \rightarrow & & \{\ \textit{offset}\ = 0; \} \\
& D & \\
D \rightarrow & T\ \textbf{id}; & \{\ \textit{top.put}(\textbf{id}.\textit{lexeme},\ \mathrm{T}.\textit{type},\ \textit{offset}); \\
& & \quad \textit{offset}\ = \textit{offset} + T.\textit{width}; \} \\
& D_1 & \\
D \rightarrow & \epsilon &
\end{array}
$$

Fields in Records and Classes

Example

```
float x;
record { float x; float y; } p;
record { int tag; float x; float y; } q;
x = p.x + q.x;
```

$$
\begin{array}{lll}
D & \rightarrow & T\ \textbf{id};D \mid \epsilon \\
T & \rightarrow & \textbf{record}\ '\{'\ D\ '\}'
\end{array}
$$

- Fields are specified by sequence of declarations
  - Field names within record must be distinct
  - Relative address for field is relative to data area for that record

Fields in Records and Classes

Stored in separate symbol table t

Record type has form *record*(t)

$$
\begin{array}{lll}
T \rightarrow & \textbf{record}\ '\{' & \{\ \textit{Env.push}(\textit{top});\ \ \textit{top} = \textbf{new}\ \textit{Env}(); \\
& & \quad \textit{Stack.push}(\textit{offset});\ \ \textit{offset} = 0; \} \\
& D\ '\}' & \{\ T.\textit{type} = \textit{record}(\textit{top});\ \ T.\textit{width} = \textit{offset}; \\
& & \quad \textit{top} = \textit{Env.pop}();\ \ \textit{offset} = \textit{Stack.pop}(); \}
\end{array}
$$

6.4 Translation of Expressions

- Temporary names are created
  $E \rightarrow E_1 + E_2$ yields $t = E_1 + E_2$, e.g.,

```
t5 = t2 + t4
 a = t5
```

- If expression is identifier, then no new temporary
- Nonterminal E has two attributes:
  - $E.\textit{addr}$ – address that will hold value of E
  - $E.\textit{code}$ – three-address code sequence

Syntax-Directed Definition

To produce three-address code for assignments

Production	Semantic Rules
$S \rightarrow \textbf{id} = E;$	$S.\textit{code} = E.\textit{code}\ \Vert$ $\textit{gen}(\textit{top.get}(\textbf{id}.\textit{lexeme})\ '='\ E.\textit{addr})$
$E \rightarrow E_1 + E_2$	$E.\textit{addr} = \textbf{new}\ \textit{Temp}()$ $E.\textit{code} = E_1.\textit{code}\ \Vert\ E_2.\textit{code}\ \Vert$ $\textit{gen}(E.\textit{addr}\ '='\ E_1.\textit{addr}\ '+'\ E_2.\textit{addr})$
$\mid -E_1$	$E.\textit{addr} = \textbf{new}\ \textit{Temp}()$ $E.\textit{code} = E_1.\textit{code}\ \Vert$ $\textit{gen}(E.\textit{addr}\ '='\ '\textbf{minus}'\ E_1.\textit{addr})$
$\mid (E_1)$	$E.\textit{addr} = E_1.\textit{addr}$ $E.\textit{code} = E_1.\textit{code}$
$\mid \textbf{id}$	$E.\textit{addr} = \textit{top.get}(\textbf{id}.\textit{lexeme})$ $E.\textit{code} =\ ''$

Translation scheme

To incrementally produce three-address code for assignments

$$
\begin{array}{lll}
S \rightarrow & \textbf{id} = E; & \{\ \textit{gen}(\textit{top.get}(\textbf{id}.\textit{lexeme})\ '='\ E.\textit{addr}); \} \\
E \rightarrow & E_1 + E_2 & \{\ E.\textit{addr} = \textbf{new}\ \textit{Temp}(); \\
& & \quad \textit{gen}(E.\textit{addr}\ '='\ E_1.\textit{addr}\ '+'\ E_2.\textit{addr}); \} \\
\mid & -E_1 & \{\ E.\textit{addr} = \textbf{new}\ \textit{Temp}(); \\
& & \quad \textit{gen}(E.\textit{addr}\ '='\ '\textbf{minus}'\ E_1.\textit{addr}); \} \\
\mid & (E_1) & \{\ E.\textit{addr} = E_1.\textit{addr}; \} \\
\mid & \textbf{id} & \{\ E.\textit{addr} = \textit{top.get}(\textbf{id}.\textit{lexeme}); \}
\end{array}
$$

Addressing Array Elements

- Array $A[n]$ with elements at positions $0, 1, \ldots, n-1$
- Let
  - w be width of array element
  - *base* be relative address of storage allocated for A $(= A[0])$

  Element $A[i]$ begins in location $\quad \textit{base} + i \times w$

- In two dimensions, let
  - w_1 be width of row,
  - w_2 be width of element of row

  Element $A[i][j]$ begins in location $\quad \textit{base} + i \times w_1 + j \times w_2$

- In k dimensions $\quad \textit{base} + i_1 * w_1 + i_2 * w_2 + \cdots + i_k * w_k$

Translation of Array References

L generates array name followed by sequence of index expressions

$$L \rightarrow L[E] \mid \textbf{id}[E]$$

Three synthesized attributes

- $L.\textit{addr}$: temporary used to compute location in array
- $L.\textit{array}$: pointer to symbol-table entry for array name
  - $L.\textit{array.base}$: base address of array
- $L.\textit{type}$: type of subarray generated by L
  - For type t: $t.\textit{width}$
  - For array type t: $t.\textit{elem}$

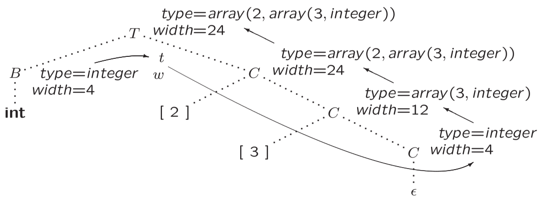
Translation of Array References

$S \rightarrow \textbf{id} = E;$	$\{ \; gen(top.get(\textbf{id}.lexeme) \; '=' \; E.addr); \}$
$S \rightarrow L = E;$	$\{ \; gen(L.array.base \; '[' L.addr \; ']' \; '=' \; E.addr); \}$
$E \rightarrow E_1 + E_2$	$\{ \; E.addr = \textbf{new} \; Temp(); \; gen(E.addr \; '=' \; E_1.addr \; '+' \; E_2.addr); \}$
$E \rightarrow \textbf{id}$	$\{ \; E.addr = top.get(\textbf{id}.lexeme); \}$
$E \rightarrow L$	$\{ \; E.addr = \textbf{new} \; Temp(); \; gen(E.addr \; '=' \; L.array.base \; '[' L.addr \; ']'); \}$
$L \rightarrow \textbf{id} \; [E]$	$\{ \; L.array = top.get(\textbf{id}.lexeme); \; L.type = L.array.type.elem; \; L.addr = \textbf{new} \; Temp(); \; gen(L.addr \; '=' \; E.addr \; '*' \; L.type.width); \}$
$L \rightarrow L_1[E]$	$\{ \; L.array = L_1.array; \; L.type = L_1.type.elem; \; t = \textbf{new} \; Temp(); \; L.addr = \textbf{new} \; Temp(); \; gen(t \; '=' \; E.addr \; '*' \; L.type.width); \; gen(L.addr \; '=' \; L_1.addr \; '+' \; t); \}$

Translation of Array References

$E \rightarrow \textbf{id}$	$\{ \; E.addr = top.get(\textbf{id}.lexeme); \}$
$L \rightarrow \textbf{id} \; [E]$	$\{ \; L.array = top.get(\textbf{id}.lexeme); \; L.type = L.array.type.elem; \; L.addr = \textbf{new} \; Temp(); \; gen(L.addr \; '=' \; E.addr \; '*' \; L.type.width); \}$
$L \rightarrow L_1[E]$	$\{ \; L.array = L_1.array; \; L.type = L_1.type.elem; \; t = \textbf{new} \; Temp(); \; L.addr = \textbf{new} \; Temp(); \; gen(t \; '=' \; E.addr \; '*' \; L.type.width); \; gen(L.addr \; '=' \; L_1.addr \; '+' \; t); \}$
$E \rightarrow L$	$\{ \; E.addr = \textbf{new} \; Temp(); \; gen(E.addr \; '=' \; L.array.base \; '[' L.addr \; ']'); \}$
$E \rightarrow E_1 + E_2$	$\{ \; E.addr = \textbf{new} \; Temp(); \; gen(E.addr \; '=' \; E_1.addr \; '+' \; E_2.addr); \}$
$S \rightarrow \textbf{id} = E;$	$\{ \; gen(top.get(\textbf{id}.lexeme) \; '=' \; E.addr); \}$
$S \rightarrow L = E;$	$\{ \; gen(L.array.base \; '[' L.addr \; ']' \; '=' \; E.addr); \}$

Types and Their Widths (Example)



Translation of Array References (Example)

- Let a be 2×3 array of integers
- Let c, i and j be integers
- Annotated parse tree for expression `c + a[i][j]`

6.6 Control Flow

- Boolean expressions used to
  1. Alter flow of control: **if** (E) S
  2. Compute logical values, cf. arithmetic expressions
- Generated by

  $B \rightarrow B||B \;|\; B\&\&B \;|\; !B \;|\; (B) \;|\; E \; \textbf{rel} \; E \;|\; \textbf{true} \;|\; \textbf{false}$
- In $B_1||B_2$, if B_1 is true, then expression is true
  In $B_1\&\&B_2$, if . . .

Short-Circuit Code

or jumping code

Boolean operators ||, && and ! translate into jumps

Example

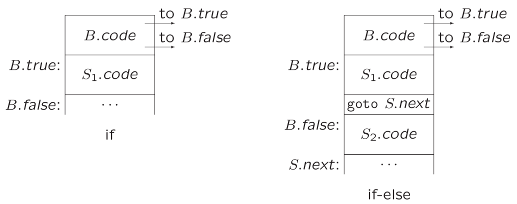
```
if ( x < 100 || x > 200 && x!=y ) x = 0;
```

Precedence: || < && < !

```
     if x < 100 goto L2
     ifFalse x > 200 goto L1
     ifFalse x != y goto L1
L2:  x = 0
L1:
```


Flow-of-Control Statements

$S \rightarrow \textbf{if} \; (B) \; S_1$
$S \rightarrow \textbf{if} \; (B) \; S_1 \; \textbf{else} \; S_2$
$S \rightarrow \textbf{while} \; (B) \; S_1$



Translation using
- synthesized attributes $B.code$ and $S.code$
- inherited attributes (labels) $B.true$, $B.false$ and $S.next$

Syntax-Directed Definition

Production	Semantic Rules
$P \rightarrow S$	$S.next = newlabel()$ $P.code = S.code \;||\; label(S.next)$
$S \rightarrow \textbf{if} \; (B) \; S_1$	$B.true = newlabel()$ $B.false = S_1.next = S.next$ $S.code = B.code \;||\; label(B.true) \;||\; S_1.code$
$B \rightarrow B_1 \| B_2$	$B_1.true = B.true$ $B_1.false = newlabel()$ $B_2.true = B.true$ $B_2.false = B.false$ $B.code = B_1.code \;||\; label(B_1.false) \;||\; B_2.code$
$B_1 \rightarrow E_1 \; \textbf{rel} \; E_2$	$B_1.code = E_1.code \;||\; E_2.code$ $\;||\; gen('\texttt{if}' \; E_1.addr \; \textbf{rel}.op \; E_2.addr \; '\texttt{goto}' \; B_1.true)$ $\;||\; gen('\texttt{goto}' \; B_1.false)$
$B_2 \rightarrow B_3 \&\& B_4$	$B_3.true = newlabel()$ $B_3.false = B_2.false$ $B_4.true = B_2.true$ $B_4.false = B_2.false$ $B_2.code = B_3.code \;||\; label(B_3.true) \;||\; B_4.code$

Avoiding Redundant Gotos

```
      if x < 100 goto L2
      goto L3
L3:   if x > 200 goto L4
      goto L1
L4:   if x != y goto L2
      goto L1
L2:   x = 0
L1:
```

Versus

```
      if x < 100 goto L2
      ifFalse x > 200 goto L1
      ifFalse x != y goto L1
L2:   x = 0
L1:
```


6.7 Backpatching

- Code generation problem:
  - Labels (addresses) that control must go to may not be known at the time that jump statements are generated
- One solution:
  - Separate pass to bind labels to addresses
- Other solution: backpatching
  - Generate jump statements with empty target
  - Add such statements to a list
  - Fill in labels when proper label is determined

Backpatching

- Synthesized attributes $B.truelist$, $B.falselist$, $S.nextlist$ containing lists of jumps
- Three functions

1. *makelist*(i) creates new list containing index i
2. *merge*(p_1, p_2) concatenates lists pointed to by p_1 and p_2
3. *backpatch*(p, i) inserts i as target label for each instruction on list pointed to by p

Grammars for Backpatching

- Grammar for boolean expressions:

$$\begin{array}{lcl} B & \rightarrow & B_1 || M B_2 \mid B_1 \&\& M B_2 \mid !B_1 \mid (B_1) \\ & & \mid E_1 \textbf{ rel } E_2 \mid \textbf{true} \mid \textbf{false} \\ M & \rightarrow & \epsilon \end{array}$$

M is marker nonterminal

- Grammar for flow-of-control statements

$$\begin{array}{lcl} S & \rightarrow & \textbf{if } (B)\ S_1 \mid \textbf{if } (B)\ S_1 \textbf{ else } S_2 \\ & \mid & \textbf{while } (B)\ S_1 \mid \{L\} \mid A; \\ N & \rightarrow & \epsilon \\ L & \rightarrow & L_1 S \mid S \end{array}$$

Example: `if (x < 100 || x > 200 && x != y) x = 0;`

Translation Scheme for Backpatching

$B \rightarrow E_1$ **rel** E_2	{ $B.truelist = makelist(nextinstr)$; $B.falselist = makelist(nextinstr + 1)$; $gen('\texttt{if}'\ E_1.addr\ \textbf{rel}.op\ E_2.addr\ '\texttt{goto \_}')$; $gen('\texttt{goto \_}')$; }
$M \rightarrow \epsilon$	{ $M.instr = nextinstr$; }
$B_2 \rightarrow B_3 \&\& M B_4$	{ $backpatch(B_3.truelist, M.instr)$; $B_2.truelist = B_4.truelist$; $B_2.falselist = merge(B_3.falselist, B_4.falselist)$; }
$B \rightarrow B_1 \|\| M B_2$	{ $backpatch(B_1.falselist, M.instr)$; $B.truelist = merge(B_1.truelist, B_2.truelist)$; } $B.falselist = B_2.falselist$;
$S \rightarrow A$	{ $S.nextlist = \textbf{null}$; }
$S \rightarrow$ **if** $(B)\ M S_1$	{ $backpatch(B.truelist, M.instr)$; $S.nextlist = merge(B.falselist, S_1.nextlist)$; }

6.8 Switch-Statements

switch (E)
{
    case V_1: S_1
    case V_2: S_2
    . . .
    case V_{n-1}: S_{n-1}
    default S_n
}

Translation:

1. Evaluate expression E
2. Find value V_j in list of cases that matches value of E
3. Execute statement S_j

Translation of Switch-Statement

```
      code to evaluate E into t
      goto test
L1:   code for S1
      goto next
L2:   code for S2
      goto next
      ...
L_{n-1}:  code for S_(n-1)
          goto next
L_{n}:    code for S_n
          goto next
test: if t = V1 goto L1
      if t = V2 goto L2
      ...
      if t = V_{n-1} goto L_{n-1}
      goto L_{n}
next:
```


Volgende week

- Maandag 29 oktober: inleveren opdracht 2
- Practicum over opdracht 3
- Eerst naar 403, daarna naar 302/304
- Inleveren 19 november

Compiler constructie

college 6
Intermediate Code Generation

Chapters for reading:
6.intro, 6.2–6.2.3, 6.3.3–6.3.6, 6.4, 6.6–6.8