Compilerconstructie

najaar 2013

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

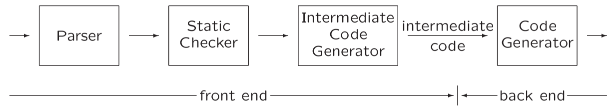
Rudy van Vliet
kamer 124 Snellius, tel. 071-527 5777
rvvliet(at)liacs(dot)nl

college 6, dinsdag 22 oktober 2013

Intermediate Code Generation

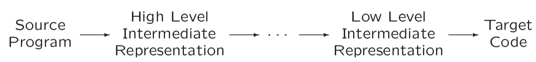
6. Intermediate Code Generation

- 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++

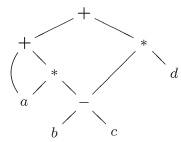


6.2 Three-Address Code

- 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	$x = \&y, \quad x = *y, \quad *x = y$

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...

Implementation of Three-Address Instructions

Quadruples: records *op*, *vararg1*, *vararg2*, *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	*vararg1*	*vararg2*	*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	*vararg1*	*vararg2*	*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*, *vararg1*, *vararg2*

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

Syntax tree. . .

Three-address code

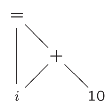
```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	op	*vararg1*	*vararg2*
0	minus	c	
1	$*$	b	(0)
2	minus	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	(4)
		. . .	

Implementation: Value-Number Method

(from college 5)

DAG for $i = i + 10$



1	**id**		
2	**num**	10	
3	$+$	1	2
4	$=$	1	3
5	. . .		

to entry for i

- Search array for (existing) node
- Use hash table

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	*vararg1*	*vararg2*
0	minus	c	
1	$*$	b	(0)
2	minus	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	(4)
		. . .	

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	*vararg1*	*vararg2*
0	minus	c	
1	$*$	b	(0)
2	minus	c	
3	$*$	b	(2)
4	$+$	(1)	(3)
5	$=$	a	(4)
		. . .	

6.4 Translation of Expressions

- Temporary names are created
  $E \to E_1 + E_2$ 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.addr* – address that will hold value of E
  - *E.code* – three-address code sequence

Syntax-Directed Definition

To produce three-address code for assignments

Production	Semantic Rules
$S \to$ **id** $= E;$	*S.code* $=$ *E.code* $\|\|$ *gen*(*top.get*(**id**.*lexeme*) $'='$ *E.addr*)
$E \to E_1 + E_2$	*E.addr* $=$ **new** *Temp*() *E.code* $=$ E_1*.code* $\|\|$ E_2*.code* $\|\|$ *gen*(*E.addr* $'='$ E_1*.addr* $'+'$ E_2*.addr*)
$\mid -E_1$	*E.addr* $=$ **new** *Temp*() *E.code* $=$ E_1*.code* $\|\|$ *gen*(*E.addr* $'='$ $'$**minus**$'$ E_1*.addr*)
$\mid (E_1)$	*E.addr* $= E_1$*.addr* *E.code* $= E_1$*.code*
$\mid$ **id**	*E.addr* $=$ *top.get*(**id**.*lexeme*) *E.code* $=$ ''

Example: $a = b + -c$

Translation scheme

To incrementally produce three-address code for assignments

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

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 $\quad base + i \times w$
- 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 $\quad base + i \times w_1 + j \times w_2$
- In k dimensions $\quad base + i_1 * w_1 + i_2 * w_2 + \cdots + i_k * w_k$

Translation of Array References

L generates array name followed by sequence of index expressions

$$L \rightarrow L[E] \;\; | \;\; \textbf{id}[E]$$

Three synthesized attributes

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

Translation of Array References

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

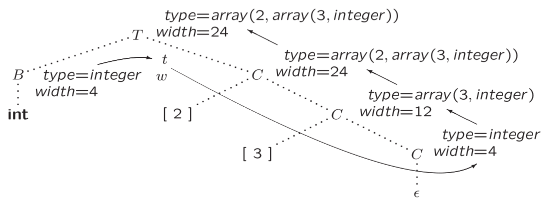
Translation of Array References

$$\begin{array}{lcll}
S & \rightarrow & \textbf{id} = E; & \{ \; gen(top.get(\textbf{id}.lexeme) \; '=' \; E.addr); \} \\
S & \rightarrow & L = E; & \{ \; gen(L.array.base \; '[' L.addr \; ']' \; '=' \; E.addr); \} \\
E & \rightarrow & E_1 + E_2 & \{ \; E.addr = \textbf{new} \; Temp(); \\
 & & & \quad gen(E.addr \; '=' \; E_1.addr \; '+' \; E_2.addr); \} \\
E & \rightarrow & \textbf{id} & \{ \; E.addr = top.get(\textbf{id}.lexeme); \} \\
E_2 & \rightarrow & L & \{ \; E_2.addr = \textbf{new} \; Temp(); \\
 & & & \quad gen(E_2.addr \; '=' \; L.array.base \; '[' L.addr \; ']'); \} \\
L_1 & \rightarrow & \textbf{id} \; [E_3] & \{ \; L_1.array \; = top.get(\textbf{id}.lexeme); \\
 & & & \quad L_1.type \; = L_1.array.type.elem; \\
 & & & \quad L_1.addr \; = \textbf{new} \; Temp(); \\
 & & & \quad gen(L.addr \; '=' \; E_3.addr \; '*' \; L.type.width); \} \\
L & \rightarrow & L_1[E_4] & \{ \; L.array \; = L_1.array; \\
 & & & \quad L.type \; = L_1.type.elem; \\
 & & & \quad t = \textbf{new} \; Temp(); \\
 & & & \quad L.addr \; = \textbf{new} \; Temp(); \\
 & & & \quad gen(t \; '=' \; E_4.addr \; '*' \; L.type.width); \\
 & & & \quad gen(L.addr \; '=' \; L_1.addr \; '+' \; t); \}
\end{array}$$

Types and Their Widths (Example)

(from college 5)

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



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

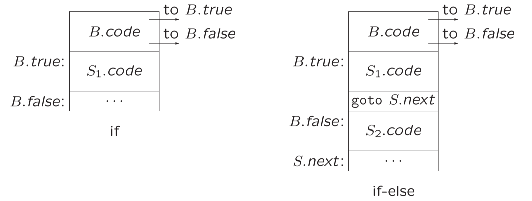
```
if ( x < 100 || x > 200 && x!=y ) x = 0;
```

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

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

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:

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

M is marker nonterminal

- Grammar for flow-of-control statements (marker nonterminals omitted for readability)

$$S \rightarrow \textbf{if}\ (B)\ S_1 \ \mid\ \textbf{if}\ (B)\ S_1\ \textbf{else}\ S_2 \ \mid\ \textbf{while}\ (B)\ S_1 \ \mid\ \{L\} \ \mid\ A;$$
$$L \rightarrow L_1 S \ \mid\ S$$

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

Translation Scheme for Backpatching

$B \rightarrow B_1 \mid\mid M B_2$ { *backpatch*(B_1.*falselist*, M.*instr*);
B.truelist = *merge*(B_1.*truelist*, B_2.*truelist*);
B.falselist = B_2.*falselist*; }

$B \rightarrow B_1 \&\& M B_2$ { *backpatch*(B_1.*truelist*, M.*instr*);
B.truelist = B_2.*truelist*;
B.falselist = *merge*(B_1.*falselist*, B_2.*falselist*); }

$B \rightarrow E_1$ **rel** E_2 { *B.truelist* = *makelist*(*nextinstr*);
B.falselist = *makelist*(*nextinstr* + 1);
gen('`if`' E_1.*addr* **rel**.*op* E_2.*addr* '`goto` _');
gen('`goto` _'); }

$M \rightarrow \epsilon$ { *M.instr* = *nextinstr*; }

$S \rightarrow$ **if** (B) MS_1 { *backpatch*(*B.truelist*, *M.instr*);
S.nextlist = *merge*(*B.falselist*, S_1.*nextlist*); }

$S \rightarrow A$ { *S.nextlist* = **null**; }

Translation Scheme for Backpatching

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

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 28 oktober: inleveren opdracht 2
- Dinsdag 29 oktober: practicum over opdracht 3
- Eerst naar 403, daarna naar 302/304
- Inleveren 18 november

Compilerconstructie

college 6
Intermediate Code Generation

Chapters for reading:
6.intro, 6.2–6.2.3, 6.4,
6.6–top-of-page-406,
6.7–6.7.3, 6.8