



5. Semantic Analysis II

Type Checking – Intermediate Code Generation

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ToC

1 Preliminaries

2 Types

3 Control Flow

Intermediate Code generation

- Last block in the front end of a compilers. To delve into the topic we need to consider:
 - **intermediate representations** – memory management is still abstracted
 - **static checking** – type checking in particular
 - **intermediate code generation** – the C programming language is often selected as an intermediate form because it is flexible, it compiles into efficient machine code, and its compilers are widely available.

Three Address Code

The term “three-address code” comes from instructions of the general form $x = y \text{ op } z$ with three addresses (two for the operands and one for the result)

In “three-address code” operations there is at most one operator on the right side of each single instruction.

Consider the expression: $x + y * z$ the codification will look like ...

Building blocks

Three address code is built from two concepts: addresses, instructions.

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Building blocks

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Founding concepts

Addresses

- ▶ name
- ▶ constant
- ▶ compiler generated temporary

Instructions

- ▶ assignment (with binary and unary operators) – e.g. $x = y \text{ op } z$, $x = \text{op } y$
- ▶ copy instructions – e.g. $x = y$
- ▶ unconditional jump – e.g. `goto L`
- ▶ conditional jump with boolean – `if x goto L, ifFalse x goto L`
- ▶ conditional jump with relational operators – `if x relop y goto L`
- ▶ procedure calls and returns – e.g. `param x, call p, n, and y = call p, n`
- ▶ indexed copy instructions – e.g. $x=y[i]$ and $x[i]=y$
- ▶ Address and pointer assignment – e.g. $x=\&y$, $x=*y$, $*x=y$

Three address code representation and storage

Let's provide a translation for the following code fragment:

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

- Quadruples – includes results
- Triples
- Indirect triples
- static single-assignment form

Direct Acyclic Graph(DAG)

A Direct Acyclic Graph (DAG) can be considered a compacted form of an AST where common terms are not repeated. The result is that “leaves” will have more than one parent resulting in a **graph rather than a tree structure**

Consider the case of the expression $a + a * (b - c) + (b - c) * d$

How to generate it

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Three address code and DAG

Three address code are **linearized representation of a syntax tree or DAG**. For instance the DAG for $a + a \times (b - c) + (b - c) \times d$ can be represented by the following three address code snippet:

$$t_1 = b - c$$

$$t_2 = a * t_1$$

$$t_3 = a * t_2$$

$$t_4 = t_1 * d$$

$$t_5 = t_3 + t_4$$

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1 Preliminaries

2 **Types**

3 Control Flow

Types and Declarations

Types establish sets in which program elements can get their values.
Two main activities related to compiling:

- ▶ **Type Checking** uses logical rules to reason about the behavior of program at run time
- ▶ **Translation Applications** in which type related information are useful to determine the memory space needed for names at run-time, to compute address denoted by array reference, to apply conversions, to determine the operators to apply ...

Type Expression

Type Expressions

A **type expression** is either a basic type or is formed by applying an operator, called **type constructor**, to a type expression. E.g. `int [2] [3]`

inductive constructions of types expressions

- ▶ A basic type is a type expression (generally languages include basic types such as – boolean, char, integer, float, void, double, ...)
- ▶ A type name is a type expression
- ▶ The **array** operator can be applied to a type expression to form a new type expression
- ▶ A **record** form a type expression from a list of type expressions
- ▶ The **function operator** (\rightarrow) can be used to define a function from a type s to type t
- ▶ The **Cartesian product** for two type expressions results in a new type expression

Declarations

Let's consider a simplified grammar for declarations:

$$D \rightarrow T \text{ id}; D \mid \epsilon \quad T \rightarrow BC \mid \text{record } \{ D \}$$

$$B \rightarrow \text{int} \mid \text{float} \quad C \rightarrow \epsilon \mid [\text{num}]C$$

Types and storage allocation

Worth to be mentioned:

- Relative addresses can be assigned at compile time
- Addressing constraints of the target machine influence assignment of addresses

Types and storage allocation for sequence of declarations

D	\rightarrow	$T \text{ id};$	{ top.put(id .lexeme, T.type, offset); offset = offset + T.width; }
		D_1	
		ϵ	
T	\rightarrow	B	{ t=B.type; w=B.width; }
		C	
		record '{'	{ Env.push(top); top = new Env(); Stack.push(offset); offset=0; }
		D '}'	{ T.type=record(top); T.width=offset; top=Env.pop(); offset=Stack.pop(); }
B	\rightarrow	int	{ B.type=integer; B.width=4; }
		float	{ B.type=float; B.width=8; }
C	\rightarrow	[num] C	{ array(num.value, C_1 .type); C .width=num.value \times C_1 .width; }
		ϵ	{ C .type = t; C .width = w; }

Translation of Expressions

In the translation of an expression we need to represent the code for the expression and the address in which the computed value will be stored. Therefore let's consider an excerpt for the usual expression grammar:

$$S \rightarrow \mathbf{id} = E \quad E \rightarrow E_1 + E_2 \mid - E_1 \mid (E_1) \mid \mathbf{id}$$

SDD for three address code translation

S	\rightarrow	id = E	$S.code = E.code \parallel$ $gen(top.get(\mathbf{id}.lexeme) '=' E.addr)$
E	\rightarrow	$E_1 + E_2$	$E.addr = \mathbf{new} Temp()$ $E.code = E_1.code \parallel E_2.code \parallel gen(E.addr '=' E_1.addr '+' E_2.addr)$
		$-E_1$	$E.addr = \mathbf{new} Temp()$ $E.code = E_1.code \parallel gen(E.addr '=' \mathbf{minus} E_1.addr)$
		(E_1)	$E.addr = E_1.addr, Ecode = E_1.code$
		id	$E.addr = top.get(\mathbf{id}.lexeme), E.code = ' '$

Consider the expression “a=b+-c” and derive the three address code translation applying the semantic rules defined

Type Checking

To do type checking is necessary to assign a type expression to each component of the source program. Then a set of logical rules (**type system**) are defined to check if any non conformity is spotted.

Type checking can take two forms:

- ▶ type synthesis
- ▶ type inference

Type Synthesis

In **type synthesis** the type of an expression is derived from **those of its sub-expressions**. **Names** need to be **declared before usage**.

A typical rule will look like the following one:

***if** f has type $s \rightarrow t$ **and** x has type s ,
then expression $f(x)$ has type t*

e.g. consider the case of $E_1 + E_2$

Type inference

W

With **type inference** the type of a construct is determined from the way it is used.

A typical rule for the type inference has the form:

if $f(x)$ is an expression,
then for some α and β , f has type $\alpha \rightarrow \beta$ and x has type α

Type conversion

Consider the expression $a = b + c$ where the variables do not necessarily have the same type....**managed via type conversion**

All languages have their specific rules defined for conversion:

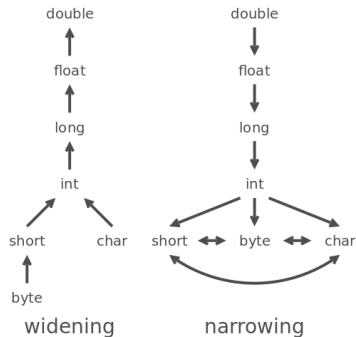
- ▶ **narrowing**
- ▶ **widening**

Type conversion

Consider the expression $a = b + c$ where the variable do not necessarily have the same type....**managed via type conversion**

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Type conversion

To define semantic actions for type checking two auxiliary functions are defined:

- $max(t_1, t_2)$
- $widen(a, t, w)$ – where a is an address, while t and w are types

```

E  →  E1 + E2  {  E.type = max(E1.type, E2.type);
                    a1 = widen (E1.addr, E1.type, E.type)
                    a2 = widen (E2.addr, E2.type, E.type)
                    E.addr = new Temp();
                    gen(E.addr '=' a1 '+' a2);  }
  
```


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Control Flow

Boolean expressions are the building block for influencing the flow of a program. They are manipulated to:

- ▶ Alter the flow of control – like in `if (E) S`
- ▶ Compute logical values

Two different approaches to evaluation:

- ▶ Eager
- ▶ Lazy

Control Flow – Boolean expressions

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	\rightarrow	$B_1 \&\& B_2$	$B_1.true = newlabel()$ $B_1.false = B.false$ $B_2.true = B.true$ $B_2.false = B.false$ $B.code = B_1.code label(B_1.true) B_2.code$
B	\rightarrow	$E_1 \mathit{rel} E_2$	$B.code = E_1.code E_2.code$ $ \text{gen('if' } E_1.addr \mathit{rel.op} E_2.addr \text{'goto' } B.true)$ $ \text{gen('goto' } B.false)$
B	\rightarrow	true	$B.code = \text{gen('goto' } B.true)$
B	\rightarrow	false	$B.code = \text{gen('goto' } B.false)$

Control Flow – commands

P	\rightarrow	S	$S.next=newlabel(), P.code = S.code \parallel label(S.next)$
S	\rightarrow	assign	$S.code=assign.code$
S	\rightarrow	if (B) S_1	$B.true=newlabel(), B.false=S_1.next=S.next$ $S.code=B.code\parallel label(B.true)\parallel S_1.code$
S	\rightarrow	if (B) S_1 else S_2	$B.true=newlabel(), B.false=newlabel()$ $S_1.next=S_2.next=S.next$ $S.code=B.code\parallel label(B.true)\parallel S_1.code$ $\parallel gen('goto' S.next)\parallel label(B.false)\parallel S_2.code$
S	\rightarrow	while (B) S_1	$begin=newlabel(), B.true=newlabel()$ $B.false=S.next, S_1.next=begin$ $S.code=label(begin)\parallel B.code\parallel label(B.true)\parallel S_1.code$ $\parallel gen('goto' begin)$
S	\rightarrow	$S_1 S_2$	$S_1.next=newlabel(), S_2.next=S.next$ $S.code = S_1.code\parallel label(S_1.next)\parallel S_2.code$

Control Flow – commands

Let's translate the following program:

```
if (x != y && x == z) x = y + z;
```