5. Semantic Analysis II

Type Checking – Intermediate Code Generation

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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 $x = y \; op \; z$ 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

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Founding concepts

Addresses

- name
- constant
- compiler generated temporary

Instructions

- assignment (with binary and unary operators) – e.g. $x = y\ op\ z$, $x = op\ y$
- 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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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 of 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:

$$D \rightarrow T\ \mathbf{id};\ D \mid \epsilon \quad T \rightarrow BC \mid \mathbf{record}\ '\{'\ D\ '\}'$$

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

`int[2][3]`

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 **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:

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

SDD for three address code translation

S	$\rightarrow$	**id** $=E$	S.code=E.code || gen(top.get(**id**.lexeme) '=' E.addr)
E	$\rightarrow$	$E_1 + E_2$	E.addr=**new** Temp() E.code = E_1.code || E_2.code || gen(E.addr '=' E_1.addr '+' E_2.addr)
	|	$-E_1$	E.addr=**new** Temp() E.code = E_1.code || gen(E.addr '=' '**minus**' E_1.addr)
	|	(E_1)	E.addr= E_1.addr, Ecode =E_1.code
	|	**id**	E.addr =top.get(**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 $s \to t$* ***and*** *x has type s,*
> ***then*** *expression $f(x)$ has type t*

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

Type inference

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ith 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 variable do not necessarily have the same type....managed via type conversion
All languages have their specific rules defined for conversion:

- narrowing
- widening

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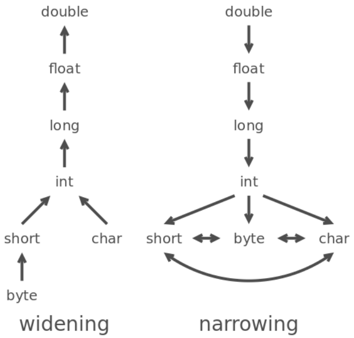

Type conversion

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

$E \rightarrow E_1 + E_2$ { E.type = max(E_1.type,E_2.type);
a$_1$ = widen (E_1.addr,E_1.type,E.type)
a$_1$ = widen (E_2.addr,E_2.type,E.type)
E.addr = **new** Temp();
gen(E.addr '=' a$_1$ '+' a$_2$); }

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

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Control Flow

Boolean expression are the building block for influencing the flow of a program. The 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**rel**E_2	B.code = E_1.code||E_2.code || gen('`if`' E_1.addr **rel**.op E_2.addr '`goto`' B.true) || gen('`goto`' B.false)
B	$\rightarrow$	**true**	B.code=gen('`goto`' B.true)
B	$\rightarrow$	**false**	B.code=gen('`goto`' B.false)

Control Flow – commands

P	$\rightarrow$	S	S.next=newlabel(), P.code = S.code || 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||label(B.true)||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||label(B.true)||S_1.code
			||gen('`goto`' S.next)|| label(B.false)|| 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)||B.code||label(B.true)||S_1.code
			||gen('`goto`' begin)

S	$\rightarrow$	S_1 S_2	S_1.next=newlabel(), S_2.next=S.next S.code = S_1.code||label(S_1.next)||S_2.code

Control Flow – commands

Let's translate the following program:

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