TDDD55 Compilers and Interpreters

TDDB44 Compiler Construction

Semantic Analysis and Intermediate Code Generation

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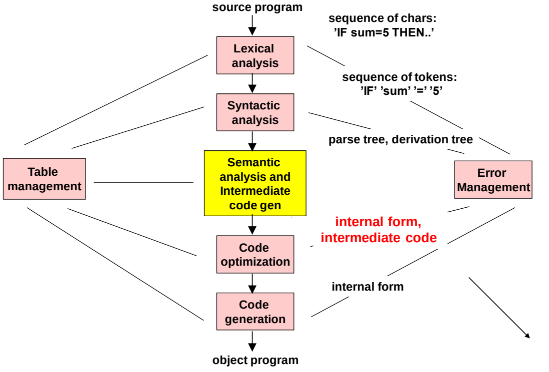
Semantic Analysis and Intermediate Code Generation



Semantic Analysis and Intermediate Representations

- The task of this phase is to check the "static semantics“ and generate the internal form of the program.
- **Static semantics**
  - Check that variables are defined, operands of a given operator are compatible, the number of parameters matches the declaration etc.
  - Formalism for static semantics?
- **Internal form**
  - Generation of good code cannot be achieved in a single pass – therefore the source code is first translated to an internal form.

Methods/Formalisms in Compiler Phases?

- **Which methods / formalisms are used in the various phases during the analysis?**
  1. Lexical analysis: *RE (regular expressions)*
  2. Syntax analysis: *CFG (context-free grammar)*
  3. Semantic analysis and intermediate code generation: *(syntax-directed translation)*

Why not the Same Formalism Everywhere?

Why not use the same formalism (formal notation) during the whole analysis?

- REs are too weak for describing the *language's syntax and semantics.*
- Both *lexical features and syntax of a language can* be described using a CFG. Everything that can be described using REs can also be described using a CFG.
- A CFG can not describe *context-dependent (static semantics) features of a language. Thus there is a* need for a stronger method of ***semantic analysis*** and the *intermediate code generation phase.*

  Syntax-directed translation is commonly used in this phase.

Use of Context Free Grammars vs Regular Expressions?

- **Follow-up questions:**
  - Why are lexical and syntax analysis divided into two different phases?
  - Why not use a CFG instead of REs in lexical descriptions of a language?
- **Answers:**
  - Simple design is important in compilers. Separating lexical and syntax analysis simplifies the work and keeps the phases simple.
  - You build a simple machine using REs (i.e. a scanner), which would otherwise be much more complicated if built using a CFG.

Syntax-Directed Translation in Semantics Phase

The first method we present for the semantics phase is **syntax-directed translation.**

Goal 1: **Semantic analysis:**

- a) Check the program to find semantic errors, e.g. type errors, undefined variables, different number of actual and formal parameters in a procedure, ...
- b) Gather information for the code generation phase, e.g.

```
var a: real;
b: integer
begin
a:= b;
...
```

generates code for the transformation:

`a := IntToReal(b);` // Note: IntToReal is a function for changing integers to a floating-point value.

Goal: Intermediate Code Generation

- Another representation of the source code is generated, a so-called intermediate code representation
- Generation of intermediate code has, among others, the following advantages:

  The internal form is:

  + machine-independent

  + not profiled for a certain language

  + suitable for optimization

  + can be used for interpreting

Examples of Internal/Intermediate forms

- **Internal forms**
  - Infix notation
  - Postfix notation (reverse Polish notation, RPN)
  - Abstract syntax trees, AST
  - Three-address code
  - Quadruples
  - Triples
- **Infix notation**
  - Example:

    a := b + c * (d + e)
  - Operands are between the operators (binary operators). Suitable notation for humans but not for machines because of priorities, associativities, parentheses.

Postfix Notation

Postfix notation
(Also called reverse Polish notation)

- Operators come after the operands.
- No parentheses or priority ordering required.
- Stack machine, compare with an HP calculator.
- Operands have the same ordering as in infix notation.
- Operators come in evaluation order.
- Suitable for expressions without conditions (e.g. if ....)

Examples and comparison:

Infix	**Postfix**
a + b	**a b +**
a + b * c	**a b c * +**
(a + b) * c	**a b + c ***
a + (-b - 3 * c)	**a b @ 3 c * - +**

Here @ denotes unary minus

Evaluation of Postfix Notation

- Given **an arithmetic expression in reverse Polish (Postfix)** notation it is easy to evaluate directly from left to right.
  - Often used in interpreters.
  - We need a **stack for storing intermediate results.**
- If numeric value:
  - Push the value onto the stack.
- If identifier:
  - Push the value of the identifier (r-value) onto the stack.
- If binary operator:
  - Pop the two uppermost elements , apply the operator to them and push the result.
- If unary operator:
  - Apply the operator directly to the top of the stack.
  - When the expression is completed, the result is on the top of the stack.

Example Evaluation of Postfix Notation

- Example: evaluate the postfix expression below.

a b @ 3 c * - +

Given that a = 34, b = 4, c = 5
corresponding infix notation: a + (-b - 3 * c)

<table>
<tr><th>Step</th><th>Stack</th><th>Input</th></tr>
<tr><td>1</td><td>-|</td><td>ab@3c*-+ |-</td></tr>
<tr><td>2</td><td>-|34</td><td>b@3c*-+ |-</td></tr>
<tr><td>3</td><td>-|34 4</td><td>@3c*-+ |-</td></tr>
<tr><td>4</td><td>-|34 -4</td><td>3c*-+ |-</td></tr>
<tr><td>5</td><td>-|34 -4 3</td><td>c*-+ |-</td></tr>
<tr><td>6</td><td>-|34 -4 3 5</td><td>*-+ |-</td></tr>
<tr><td>7</td><td>-|34 -4 15</td><td>-+ |-</td></tr>
<tr><td>8</td><td>-|34 -19</td><td>+ |-</td></tr>
<tr><td>9</td><td>-|15</td><td>|-</td></tr>
</table>

Extending Polish/Postfix Notation Assignment Statement

- **Assignment**
  - := binary operator,
  - lowest priority for infix form,
  - uses the l-value for its first operand
- Example:

x := 10 + k * 30

⇓

x 10 k 30 * + :=

Extending Polish/Postfix Notation Conditional Statement

- We need to introduce the unconditional jump, JUMP, and the conditional jump, JEQZ, Jump if EQual to Zero, and also we need to specify the jump location, LABEL.

```
L1 LABEL (or L1: )
<label> JUMP
<value> <label> JEQZ
(value = 0 ⇒ false, otherwise ⇒ true)
```

Example 1:

```
IF <expr> THEN <statement1> ELSE <statement2>
```

gives us

```
<expr> L1 JEQZ <statement1> L2 JUMP L1: <statement2> L2:
```

where L1: stands for L1 LABEL

Example 2, Postfix Notation for If-then-Else Statements

```
if a+b then
  if c-d then
    x := 10
  else y := 20
else z := 30;
```

gives us

```
a b + L1 JEQZ
c d - L2 JEQZ
x 10 := L3 JUMP
L2: y 20 := L4 JUMP
L1: z 30 := L3: L4:
```


Small Postfix Notation Exercise

Representing While Suitable Data Structure for Postfix Code

while *<expr>* ***do*** *<stat>*

gives us

L2: *<expr> L1 JEQZ <stat> L2 JUMP L1:*

Exercise

Translate the **repeat** and **for** statements to postfix notation.

Suitable data structure for postfix code

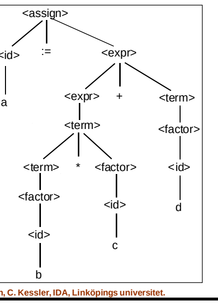
An *array where label corresponds to index.*

Array Elements:

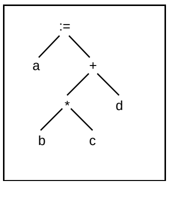
- Operand – pointer to the symbol table.
- Operator – a numeric code, for example, which does not collide with the symbol table index.

Abstract Syntax Trees (AST)

- ASTs are a reduced variant of parse trees. A parse tree contains redundant information, see the figure below.
- **Example: Parse tree for a := b * c + d**



Abstract syntax tree for a := b * c + d :



Properties of Abstract Syntax Trees

- Advantages and disadvantages of abstract syntax trees
  + Good to perform optimization on
  + Easy to traverse
  + Easy to evaluate, i.e. suitable for interpreting
  + *unparsing (prettyprinting) possible via inorder traversal*
  + *postorder traversing gives us postfix notation!*
  − Far from machine code

Three-address Code and Quadruples

Three-address code

- op: = +, -, *, /, :=, JEQZ, JUMP, [ ]=, =[ ]

```
Z    := x   op   y
↑         ↑        ↑
addr1 addr2  addr3
```

Quadruples

- Form:

  Example: Assignment statement
  A := B * C + D
- gives us the quadruples
  T1 := B * C
  T2 := T1 + D
  A := T2
- T1, T2 are temporary variables.
- The contents of the table are references to the symbol table.

Quadruples:

```
op arg1 arg2 res
```

op	arg1	arg2	res
*	B	C	T1
+	T1	D	T2
:=	T2		A

Control Structures Using Quadruples

- Example:
  if a = b
  then x := x + 1
  else y := 20;

Quad-no	op	arg1	arg2	res
1	=	a	b	T1
2	JEQZ	T1		(6) †
3	+	x	1	T2
4	:=	T2		x
5	JUMP			(7) †
6	:=	20		y
7				

† The jump address was filled in later as we can not know in advance the jump address during generation of the quadruple in a phase. We reach the addresses either during a later pass or by using syntax-directed translation and filling in when these are known. This is called **backpatching.**

Procedure call

- Example:f(a1, a2, ..., an)

Quad-no	op	arg1	arg2	res
1	param	a1		
2	param	a2		
...	...	...		
n	:=	an		
n+1	call	f	n	

- Example: READ(X)

Quad-no	op	arg1	arg2	res
1	param	X		
2	call	READ	1	

- Example: WRITE(A*B, X+5)

Quad-no	op	arg1	arg2	res
1	*	A	B	T1
2	+	X	5	T2
3	param	T1		
4	param	T2		
5	call	WRITE	2	

Array-reference

A[I] := B

[ ]= is called l-value, specifies the address to an element. In l-value context we obtain storage adress from the value of T1.

Quad-no	op	arg1	arg2	res
1	[]=	A	I	T1
2	:=	B		T1

B := A[I]

=[ ] is called r-value, specifies the value of an element

Quad-no	op	arg1	arg2	res
1	=[]	A	I	T2
2	:=	T2		B

Quadruples vs triples
Triples (also called two-address code)

Triples Form:

- *Example: A * B + C*
- No temporary name!

Triple-no	op	arg1	arg2
1	*	A	B
2	+	(1)	C

Quadruples:

− Temporary variables take up space in the symbol table.
+ Good control over temporary variables.
+ Easier to optimize and move code around.

Triples:

− Know nothing about temporary variables.
+ Take up less space.
− optimization by moving code around is difficult; in this case indirect triples are used.

Methods for Syntax-Directed Translation 1. Attribute Grammars

There are two main methods:

1. Attribute grammars, *'attributed translation grammars'*

- Describe the translation process using
  - a) CFG
  - b) a number of attributes that are attached to terminal and nonterminal symbols, and
  - c) a number of semantic rules that are attached to the rules in the grammar which calculate the value of the attribute.

2. Syntax Directed Translation Scheme

Describe the translation process using:

a) a CFG

b) a number of semantic operations

e.g. a rule: **`A → XYZ {semantic operation}`**

- Semantic operations are performed:
  - when **reduction** occurs (bottom-up), or
  - during **expansion** (top-down).
- This method is a more procedural form of the previous one (contains implementation details), which explicitly show the evaluation order of semantic rules.

Example 1: Translation Schema for *Semantic Analysis*

- **Intuition**: Attach **semantic actions** to syntactic rules to perform *semantic analysis and intermediate code generation.*
- Part of CFG, variable declarations of a language with non-nested blocks.
- The text in ***{}*** *stands for a* ***description of the semantic analysis*** for book-keeping of information on symbols in the symbol table.

<decls> → ...
<decl> → var <name-list> : <type-id>
{Attach the type of <type-id> to all id in <name-list>}
<name-list> → <name-list> , <name>
{Check that name in <name-list> is not duplicated, and check that name has not been declared previously}
<name-list> → <name>
{Check that name has not been declared previously}
<type-id>→ "ident"
{Check in the symbol table for "ident", return its index if it is already there, otherwise error: unknown type.}
<name>→ "ident"
{Update the symbol table to contain an entry for this "ident"}

Example 2: Translation Schema *Intermediate Code Generation*

Translation of **infix** notation **to postfix** notation in a bottom-up environment.

Translation of the input string:

a + b * d

becomes in postfix:

a b d * +

See the parse tree on the coming page:

Productions	Semantic operations
1 E → E1 + T	{print('+')}
2 | T	. . .
3 T → T1 * F	{print('*')}
4 | F	. . .
5 F → (E)	. . .
6 | id	{print(id)}

Translation Schema *Intermediate Code Generation*, Implementation in LR Case

The parser routine:

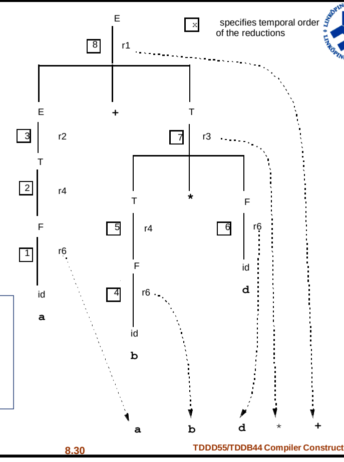
```
void parser();
{
  while not done {
   switch action {
    case shift:
    ...
    case reduce:
     semantic(ruleNo);
    ...
   }/* switch */;
  }/* while */;
}/* parser */;
```

The semantic routine:

```
void semantic(int ruleNo);
{
  switch ruleNo {
   case 1: print('+');
   case 3: print('*');
   case 6: print(id);
  };
};
```

Productions	Semantic operations
1 E → E1 + T	{print('+')}
2 | T	. . .
3 T → T1 * F	{print('*')}
4 | F	. . .
5 F → (E)	. . .
6 | id	{print(id)}

Parse Tree of Translation to Postfix Code



Translation of the input string:

a + b * d

to postfix:

a b d * +

Productions	Semantic operations
1 E → E1 + T	{print('+')}
2 | T	. . .
3 T → T1 * F	{print('*')}
4 | F	. . .
5 F → (E)	. . .
6 | id	{print(id)}

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Syntax-directed translation of assignment statements and arithmetic expressions into quadruples

using a bottom-up approach

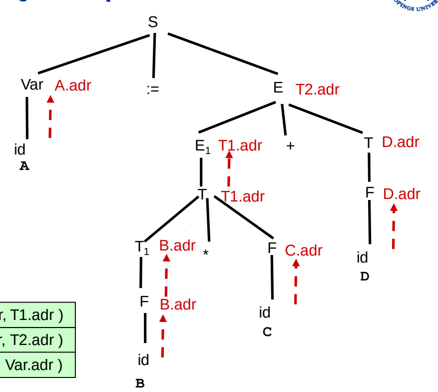
Peter Fritzson, Christoph Kessler, IDA, Linköpings universitet, 2014

Generating Quadruples

	op	opnd1	res

1. S → Var := E	{ GEN(ASGN, E.adr, 0, Var.adr); }
2. E → E_1 + T	{ temp = gen_tempvar(); GEN(ADD, E1.adr, T.adr, temp); E.adr = temp; }
3.	T	{ E.adr = T.adr; }
4. T → T_1 * F	{ temp = gen_tempvar(); GEN(MUL, T_1.adr, F.adr, temp); T.adr = temp; }
5.	F	{ T.adr = F.adr; }
6. F → (E)	{ F.adr = E.adr; }
7.	id	{ F.adr = lookup(id.name); }
8. Var → id	{ Var.adr = lookup(id.name); }

Generating Quadruples for A := B * C + D



(MUL, B.adr, C.adr, T1.adr)
(ADD, E1.adr, T.adr, T2.adr)
(ASGN, E1.adr, 0, Var.adr)

Generating Quadruples for Control Structures Example: IF-THEN-ELSE

- S → **if** E **then** S_1 **else** S_2
  - Jump to S_2 if E is false/zero
  - After S_1 jump to after S_2
- Problem: jump target quadruple indices q+1, r are unknown when the jumps are generated
- Solution: factorise the grammar, store jump index in attribute `quad`

Index	Quadruple Table
in:	Quadruples for ....
	.... temp := E
p:	<JEQZ, temp, q+1, 0>
	Quadruples for ...
	... statement S1
q:	<JUMP, r, 0, 0>
q+1: (L1:)	Quadruples for ...
	... statement S2
r: (L2:)	...

Generate Quadruples for if-then-else (2)

- Factorised grammar:
  1. <ifstmt> ::= <truepart> S_2
  2. <truepart> ::= <ifclause> S_1 **else**
  3. <ifclause> ::= **if** E **then**

Attributes:

addr = address to the symbol table entry for result of E

quad = quadruple number

Generate quadruples for if-then-else (3)

3. <ifclause> ::= **if** E **then**

```
{ <ifclause>.quad = currentquad + 1;
  // save address p of jump over S1 for later in <ifclause>.quad
  GEN ( JEQZ, E.addr, 0,    0 );
  // jump to S2.  Target q+1 not known yet.
}
```

2. <truepart> ::= <ifclause> S_1 **else**

```
{ <truepart>.quad = currentquad + 1;
  // save address q of jump over S2 for later
  GEN ( JUMP, 0,     0,    0 );
  // jump over S2.  Target r not known yet.
  QUADRUPLE[ <ifclause>.quad ][ 2 ] = currentquad + 1;
  // backpatch JEQZ target to q+1
}
```

3. <ifstmt> ::= <truepart> S_2

Generate Quadruples for if-then-else (4)

3. <ifclause> ::= **if** E **then**
   …
2. <truepart> ::= <ifclause> S_1 **else**
   { <truepart>.quad = currentquad + 1;
   // save address q of jump over S_2 for later
   GEN (JUMP, 0, 0, 0);
   // jump over S_2. Target r not known yet.
   QUADRUPLE[<ifclause>.quad][2] = currentquad + 1;
   // **backpatch JEQZ target to q+1**
   }
1. <ifstmt> ::= <truepart> S_2
   { QUADRUPLE[<truepart>.quad][1] = currentquad + 1;
   // **backpatch JUMP target to (r-1)+1**
   }

Similarly: while statement, repeat statement …

Generate Quadruples for a while statement

```
WHILE <E> DO <S>
in: quadruples for Temp := <E>
p:  JEQZ Temp q+1 Jump over <S> if <E> false
    quadruples for <S>
q:  JUMP in Jump to the loop-predicate
q+1: ...
```

The grammar factorises on:

```
1. <while-stat> ::= <while-clause> <S>
2. <while-clause>::= <while> <E> DO
3. <while> ::= WHILE
```

An extra attribute, NXTQ, must be introduced here. It has the same meaning as QUAD in the previous example.

```
3. {<while>.QUAD ::= NEXTQUAD}
```

Rule to find start of <E>

```
2. {<while-clause>.QUAD := <while>.QUAD;
```

Move along start of <E>

```
<while-clause>.NXTQ := NEXTQUAD;
```

Save the address to the next quadruple.

```
GEN(JEQF, <E>.ADDR, 0, 0)
```

Jump position not yet known! }

```
1. {GEN(JUMP, <while-clause>.QUAD,0,0);
```

Loop, i.e. jump to beginning <E>

```
QUADR[<while-clause>.NXTQ,3]:=NEXTQUAD
```

(**backpatch**) Position at the end of <S> }

Small Quadruple Generation Exercise

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Attribute Grammars

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Attribute Grammar

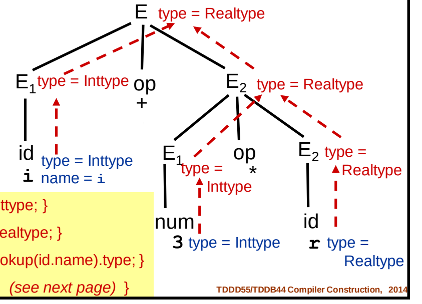
Extended context-free grammar (CFG):

- **Attribute(s)** (value fields) for each nonterminal
- **Semantic rule(s)** for each production
  - equational computation on attributes
  - executed at ***reduce*** (LR parsing) or ***expand*** (LL parsing)

- **Inherited Attributes**
  - Information propagated from left to right in a production and ***downwards*** in a parse tree
  - E.g., type in declarations, addresses of variables
- **Synthesized Attributes**
  - Information propagated from right to left in a production and ***upwards*** in a parse tree
  - E.g., value of expressions, type of expressions, transl. to internal form

Attribute Grammar Example 1
Semantic Analysis – Type Inference

- Given: Attribute Grammar, Parse tree for string **i+3*r**
- Compute: Type for each subexpression (nonterminal)



Synthesized attribute: *type*

Grammar rules:	*Semantic rules:*
E → num	{ E.type = Inttype; }
E → num . num	{ E.type = Realtype; }
E → id	{ E.type = lookup(id.name).type; }
E → E_1 op E_2	{ E.type = … *(see next page)* }

(cont.)

- Attribute grammar for syntax-directed type checking

E → num	{ E.type = Inttype; }
E → num . num	{ E.type = Realtype; }
E → id	{ E.type = lookup(id.name).type; }
E → E_1 op E_2	{ E.type = (E_1.type == Inttype && E_2.type == Inttype)? Inttype : (E_1.type == Inttype && E_2.type == Realtype || E_1.type == Realtype && E_2.type == Inttype || E_1.type == Realtype && E_2.type == Realtype) ? Realtype : error("Type error"), Notype; }

type is a synthesised attribute:
information flows right-to-left, bottom-up

(cont.)

- Attribute grammar extended for assignment statement with implicit type conversion from integer to Real

```
...             ...
E → E1 op E2    { E.type = ... }
...
S → V := E      { if  (V.type == E.type)
                     ... // generate code directly according to type
                  else
                     if (V.type == Inttype && E.type == Realtype)
                        error("Type error");
                     else
                        if (V.type == Realtype && E.type == Inttype)
                           // Code generation / evaluation with type conversion:
                           E.value = ... ;
                           V.value = ConvertIntToReal( E.value );
                        }
                }
```


Attribute Grammar Example 2: Intermediate Code Generation

- Given: Attribute grammar G
- Translate expressions in the language over G(E) to intermediate code in postfix notation
- For example: 2+3-5 is translated to: 23+5- or 235-+ depending on parse tree
- The attribute *code* is attached to all nonterminals in the grammar
- A semantic rule attached to each grammar rule

E → E_1 + E_2	{ E.code = concat(E_1.code, E_2.code, "+"); }
| E_1 – T	{ E.code = concat(E_1.code, T.code, "-"); }
| T	{ E.code = T.code; }
T → '0'	{ T.code = "0"; }
| '1'	{ T.code = "1"; }
...	...
| '9'	{ T.code = "9"; }

Attribute grammar example 3: Calculator (an interpreter of expressions)

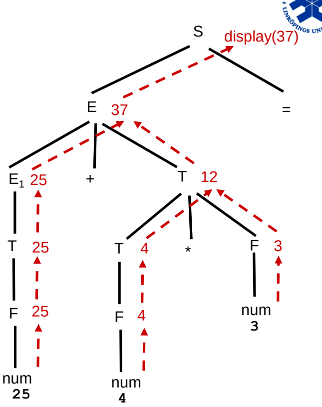
- Semantic rules calculate the value of an arithmetic expression without generating any intermediate code
- Semantic rules execute at grammar rule reductions (LR)
- Synthesised attribute N.val for each nonterminal N

S → E =	{ display(E.val); }
E → E_1 + T	{ E.val = E_1.val + T.val); }
| T	{ E.val = T.val; }
T → T_1 * F	{ T.val = T_1.val * F.val); }
| F	{ T.val = F.val; }
F → (E)	{ F.val = E.val; }
| num	{ F.val = num.val; }

value of integer-constant token num as computed by the scanner

(cont.)

- Calculator input:
  `25 + 4 * 3 =`



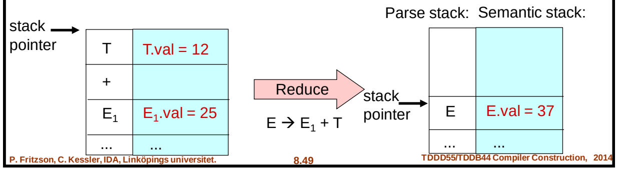
S → E =	{ display(E.val); }
E → E_1 + T	{ E.val = E_1.val + T.val); }
| T	{ E.val = T.val; }
T → T_1 * F	{ T.val = T_1.val * F.val); }
| F	{ T.val = F.val; }
F → (E)	{ F.val = E.val; }
| num	{ F.val = num.val; }

Small Attribute Grammar Exercise

LR Implementation of Attribute Grammars

- **In an LR parser:**
  - Semantic stack in parallel with the parse stack (common stack pointer)
    - Each entry can store all attributes of a nonterminal
  - When performing a reduction $[A \rightarrow \beta_1 \beta_2 \ldots \beta_k .]$
    - calculate all attributes attr by

      $A.attr = f(\beta_1.attr, \ldots, \beta_k.attr)$



LR Implementation of Attribute Grammars

- **In an LR parser (comment to picture on the previous slide)**
  - A semantic action: **E.val = E1.val +T.val**
    translated to
    a statement: **val[stkp-2] = val[stkp-2]+val[stkp]**
  - Comments:
    - stkp denotes the stack pointer, val the attribute value (an array)
    - its value in the semantic action is the value *before* the reduction
    - Af the call, the LR parser will reduce stkp by the length of the right hand side of grammar rule (here: 3)
    - It then puts E on the parse stack (because we reduced with $E = E_1+T$) with the result that the stack pointer increases a step and we get the reduced configuration in the previous slide.

LR Implementation of Attribute Grammars

Generated semantic routine:

```
semantic(ruleno)
{ switch ruleno
case 1: display(val[stkp-1]);
case 2: val [stkp-2] = val [stkp-2] + val[stkp];
case 3: ;
case 4: val[stkp-2] = val[stkp-2] * val[stkp];
case 5: ;
case 6: val[stkp-2] = val[stkp-1];
case 7: val[stkp] = num.val;
}
```

Grammar:

1. $S \rightarrow E =$
2. $E \rightarrow E_1 + T$
3. $\quad | \; T$
4. $T \rightarrow T_1 * F$
5. $\quad | \; F$
6. $F \rightarrow (E)$
7. $\quad | \; num$

- stkp specifies the stack pointer before reducing
- The stack grows with higher addresses
- reduce pops with stkp := stkp – lengthRightHandSide(rule)

Implementation of Attribute Grammars

- **In a Recursive Descent Parser:**
  - Recall: One procedure for each nonterminal
  - **Interpretation**:
    - Add a *formal parameter* for each attribute
      - implicit semantic stack (i.e., by *parameters* stored on the normal program execution stack)
      - parameters for synthesized attributes to be passed by reference, so values can be returned
  - **Code generation:**
    - Write the translated code to a memory buffer or file or return a pointer to generated code block to caller

Example: Calculator for Recursive Descent

LL(1) grammar for calculator (EBNF style):

$S \rightarrow E =$	{ display(E.val); }
$E \rightarrow T_1$	{ $E.val = T_1.val$; }
$\{+ T_2\}$	{ $E.val = E.val + T_2.val$; }
$T \rightarrow F_1$	{ $T.val = F_1.val$; }
$\{* F_2\}$	{ $T.val = E.val * F_2.val$; }
$F \rightarrow (E)$	{ F.val = E.val; }
$\mid$ num	{ F.val = num.val; }

```
void E ( int *E_val )
{
  int T1_val, T2_val;
  T ( &T1_val );
  *E_val = T1_val;
  while (token == '+') {
     scan();
     T ( &T2_val );
     *E_val = *E_val +T2_val;
  }
}
```