## Compiler construction in4303 – answers

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## Compiler construction in4303 – lecture 1

Introduction
Lexical analysis by hand

Chapter 1 – 2.15

## AST exercise (5 min.)

- expression grammar

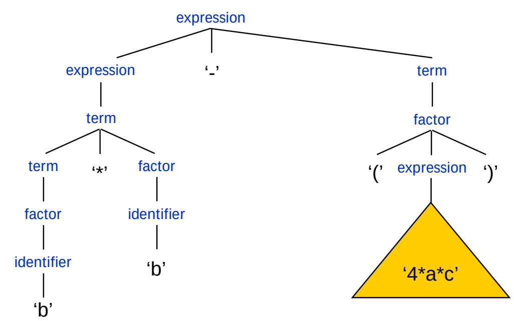
  expression → expression '+' term | expression '-' term | term
  term → term '*' factor | term '/' factor | factor
  factor → identifier | constant | '(' expression ')'

- example expression

  b*b – (4*a*c)

- draw parse tree and AST

## answer parse tree: b*b – (4*a*c)




## Exercise (5 min.)

- write down regular descriptions for the following descriptions:
  - an integral number is a non-zero sequence of digits optionally followed by a letter denoting the base class (b for binary and o for octal).
  - a fixed-point number is an (optional) sequence of digits followed by a dot ('.') followed by a sequence of digits.
  - an identifier is a sequence of letters and digits; the first character must be a letter. The underscore _ counts as a letter, but may not be used as the first or last character.

## Answers

*base* → [bo]
*integral_number* → *digit+ base?*

*dot* → [.]
*fixed_point_number* → *digit* dot digit+*

*letter* → [a-zA-Z]
*digit* → [0-9]
*underscore* → [_]
*letter_or_digit* → *letter* | *digit*
*letter_or_digit_or_und* → *letter*_or_*digit* | *underscore*
*identifier* → *letter* (*letter_or_digit_or_und** *letter_or_digit*)?

## Compiler construction
## in4303 – lecture 2

Automatic lexical analysis

Chapter 2.1.6 - 2.1.13

## FSA exercise (6 min.)

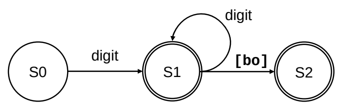
- draw an FSA to recognize integers

  *base* → [bo]
  *integer* → *digit+ base?*

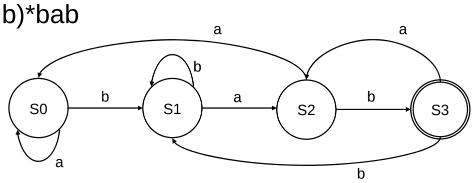
- draw an FSA to recognize the regular expression (a|b)*bab

## Answers

- integer




- (a|b)*bab




## Exercise
## FSA construction (7 min.)

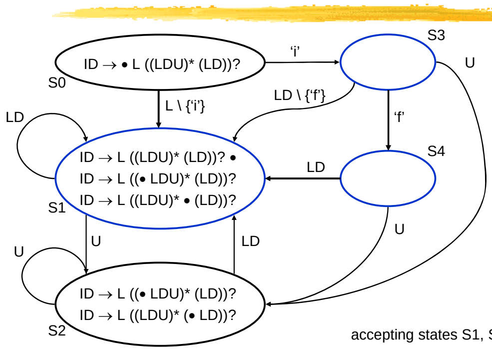
- draw the FSA (with item sets) for recognizing an identifier:

  *identifier* → *letter (letter_or_digit_or_und* letter_or_digit)?*

- extend the above FSA to recognize the keyword 'if' as well.

  *if* → 'i' 'f'

## Answers




accepting states S1, S3, and S4

## Compiler construction
## in4303 – lecture 3

Top-down parsing

Chapter 2.2 - 2.2.4

## Exercise (4 min.)

- determine the FIRST set of the non-terminals in our expression grammar

  input → expression EOF
  expression → term rest_expression
  term → IDENTIFIER | '(' expression ')'
  rest_expression → '+' expression | ε

- and, for this grammar

  S → A B
  A → A a | ε
  B → B b | b

## Answers

- FIRST(input) = { IDENT, '(' }
  FIRST(expression) = { IDENT, '(' }
  FIRST(term) = { IDENT, '(' }
  FIRST(rest_expression) = { '+', ε }

- FIRST(S) = { 'a', 'b' }
  FIRST(A) = { 'a', ε }
  FIRST(B) = { 'b' }

## Exercise (4 min.)

- determine the FIRST set of the non-terminals in our expression grammar

  input → expression EOF
  expression → term rest_expression
  term → IDENTIFIER | '(' expression ')'
  rest_expression → '+' expression | ε

- and, for this grammar

  S → A B
  A → A 'a' | ε
  B → B 'b' | 'b'

## Answers

- FIRST(input) = { IDENT, '(' }
  FIRST(expression) = { IDENT, '(' }
  FIRST(term) = { IDENT, '(' }
  FIRST(rest_expression) = { '+', ε }

- FIRST(S) = { 'a', 'b' }
  FIRST(A) = { 'a', ε }
  FIRST(B) = { 'b' }

## Exercise (7 min.)

- make the following grammar LL(1)

  expression → expression '+' term | expression '-' term | term
  term → term '*' factor | term '/' factor | factor
  factor → '(' expression ')' | func-call | identifier | constant
  func-call → identifier '(' expr-list? ')'
  expr-list → expression (',' expression)*

- and what about

  S → if E then S (else S)?

## Answers

- substitution
  F → '(' E ')' | ID '(' expr-list? ')' | ID | constant
- left factoring
  E → E ( '+' | '-' ) T | T
  T → T ( '*' | '/' ) F | F
  F → '(' E ')' | ID ( '(' expr-list? ')' )? | constant
- left recursion removal
  E → T (( '+' | '-' ) T )*
  T → F (( '*' | '/' ) F )*

- if-then-else grammar is ambiguous

# Compiler construction
# in4303 – lecture 4

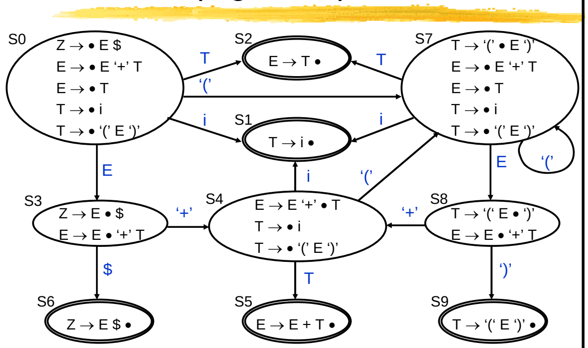
Bottom-up parsing

Chapter 2.2.5

## Exercise (8 min.)

- complete the transition diagram for the LR(0) automaton
- can you think of a single input expression that causes all states to be used? If yes, give an example. If no, explain.

## Answers (fig 2.89)




## Answers

The following expressions exercise all states

( i + i ) $
( i ) + I $
i + ( i ) $
…

## Exercise (6 min.)

- derive the SLR(1) ACTION/GOTO table (with shift-reduce conflict) for the grammar:

S → A | x b
A → a A b | x

## Answers

| | stack symbol / look-ahead token | | | | |
|---|---|---|---|---|---|
| state | a | b | x | $ | A |
| 0 | s4 | | s1 | | s3 |
| 1 | | s2/r4 | | r4 | |
| 2 | | | | r2 | |
| 3 | | | | r1 | |
| 4 | s4 | | s5 | | s6 |
| 5 | | r4 | | r4 | |
| 6 | | s7 | | | |
| 7 | | r3 | | r3 | |

1: S → A
2: S → x b
3: A → a A b
4: A → x

FOLLOW(S) = {$}
FOLLOW(A) = {$,b}

## Compiler construction in4303 – lecture 5

Semantic analysis
Assignment #1

Chapter 6.1

## Exercise (3 min.)

complete the table

| expression construct | result kind (lvalue/rvalue) |
|---|---|
| constant | rvalue |
| variable | |
| identifier (non-variable) | |
| &lvalue | |
| *rvalue | |
| V[rvalue] | |
| rvalue + rvalue | |
| lvalue = rvalue | |

V stands for lvalue or rvalue

## Answers

complete the table

| expression construct | result kind (lvalue/rvalue) |
|---|---|
| constant | rvalue |
| variable | lvalue |
| identifier (non-variable) | rvalue |
| &lvalue | rvalue |
| *rvalue | lvalue |
| V[rvalue] | V |
| rvalue + rvalue | rvalue |
| lvalue = rvalue | rvalue |

V stands for lvalue or rvalue

## Exercise (5 min.)

```
%token DIGIT
%token REG
%right '='
%left '+'
%left '*'
%%
expr : REG '=' expr        {        ??        }
     | expr '+' expr       { $$ = $1 + $3;}
     | expr '*' expr       { $$ = $1 * $3;}
     | '(' expr ')'        { $$ = $2;}
     | REG                 {        ??        }
     | DIGIT
     ;
%%
```

Extend the interpreter to a desk calculator with registers named a – z. Example input: v=3*(w+4)

## Answers

```
%{
int reg[26];
%}
%token DIGIT
%token REG
%right '='
%left '+'
%left '*'
%%
expr : REG '=' expr     { $$ = reg[$1] = $3;}
     | expr '+' expr    { $$ = $1 + $3;}
     | expr '*' expr    { $$ = $1 * $3;}
     | '(' expr ')'     { $$ = $2;}
     | REG              { $$ = reg[$1];}
     | DIGIT
     ;
%%
```

## Answers

```
%%

yylex()
{   int c = getchar();

    if (isdigit(c)) {
        yylval = c - '0';
        return DIGIT;
    } else if ('a' <= c && c <= 'z') {
        yylval = c - 'a';
        return REG;
    }
    return c;
}
```

## Exercise (5 min.)

```
eval( Expr *e)
{

        ???

}
```

- write the code to evaluate an expression

## Answers

```
eval( Expr *e)
{       static int reg[26];

        switch (e->type) {
          case EXPR_REG:
                return reg[e->reg];

          case EXPR_DIG:
                return e->dig;

          case EXPR_BIN:
                switch (e->op) {
                  case '=': return reg[e->reg] = eval(e->right);
                  case '+': return eval(e->left) + eval(e->right);
                  case '*': return eval(e->left) * eval(e->right);
                }
        }
}
```

## Compiler construction in4303 – lecture 6

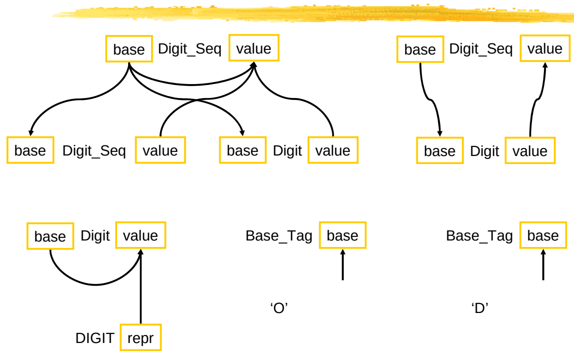
AST processing
attribute grammars

Chapter 3.1

## Exercise (5 min.)

- draw the other dependency graphs for the integral-number attribute grammar

## Answers




## Exercise (4 min.)

WHILE Number.value is not set:
walk number(Number);

- how many tree walks are necessary to evaluate the attributes of the AST representing the octal number '13O' ?
- how many for '1234D' ?

## Answers

- any integral number can be evaluated with two walks

## Compiler construction in4303 – lecture 7

AST processing
manual methods

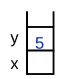
Chapter 3.2

## Exercise (5 min.)

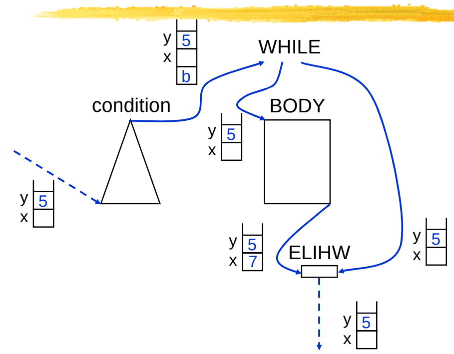
- draw the control flow graph for

  **while** C **do** S **od**

- propagate initial stack when C represents y>x and S stands for x=7




## Answers




## Exercise (5 min.) + Answers

- determine the KILL and GEN sets for the property "V is live here" for the following statements

| statement S | KILL | GEN |
|---|---|---|
| v = a ⊕ b | {v} | {a,b} |
| v = M[i] | {v} | {i} |
| M[i] = v | {} | {i,v} |
| f($a_1$, ... ,$a_n$) | {} | {$a_1$, ... ,$a_n$} |
| v = f($a_1$, ... ,$a_n$) | {v} | {$a_1$, ... ,$a_n$} |
| **if** a>b **then** goto $L_1$ **else** goto $L_2$ | {} | {a,b} |
| L: | {} | {} |
| goto L | {} | {} |

## Exercise (7 min.)

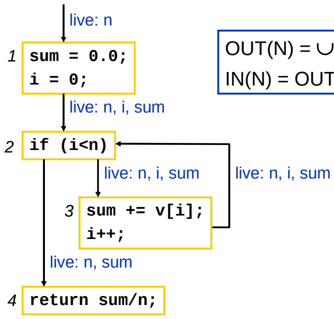
- draw the control-flow graph for the following code fragment

```
double average(int n, double v[])
{  int i;
   double sum = 0.0;

   for (i=0; i<n; i++) {
      sum += v[i];
   }
   return sum/n;
}
```

- perform backwards live analysis using the KILL and GEN sets from the previous exercise

## Answers




$OUT(N) = \cup_{M \in successor[N]} IN(M)$
$IN(N) = OUT(N) \setminus KILL(N) \cup GEN(N)$

| statement | KILL | GEN |
|---|---|---|
| 1 | sum, i | |
| 2 | | i, n |
| 3 | sum, i | sum, i |
| 4 | | sum, n |

## Answers

process nodes top to bottom (from 0 to 4)

| statement | | | iteration 1 | | iteration 2 | | iteration 3 | |
|---|---|---|---|---|---|---|---|---|
| | KILL | GEN | OUT | IN | OUT | IN | OUT | IN |
| 0 | | | | | | | n | |
| 1 | sum, i | | | | i, n | n | i, n, sum | n |
| 2 | | i, n | | i, n | i, n, sum | i, n, sum | i, n, sum | i, n, sum |
| 3 | sum, i | sum, i | i, n | i, n, sum | i, n, sum | i, n, sum | i, n, sum | i, n, sum |
| 4 | | sum, n | | n, sum | | n, sum | | n, sum |

processing nodes in reverse (from 4 to 0) requires only two iterations

## Compiler construction
## in4303 – lecture 8

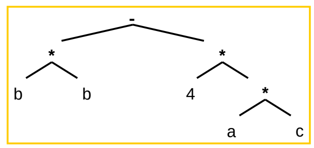
Interpretation
Simple code generation

Chapter 4 – 4.2.4

## Exercise (5 min.)

- generate code for the expression

b*b – 4*a*c




on a register machine with 32 registers numbered R1 .. R32

## Answers

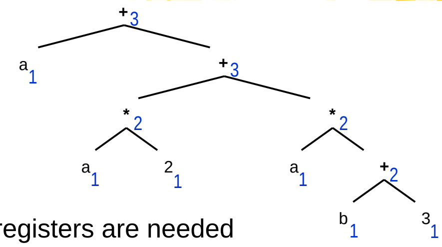
```
Load_Mem b, R1
Load_Mem b, R2
Mul_Reg R2, R1
Load_Const 4, R2
Load_Mem a, R3
Load_Mem c, R4
Mul_Reg R4, R3
Mul_Reg R3, R2
Sub_Reg R2, R1
```

## Exercise (4 min.)

- determine the number of registers needed to evaluate the expression

a + a*2 + a*(b+3)

## Answers




- three registers are needed
- but only two if you apply left-factoring!

  a + a*2 + a*(b+3) = a*(b+6)

## Compiler construction in4303 – lecture 9

Code generation

Chapter 4.2.5, 4.2.7, 4.2.11 – 4.3

## Exercise (5 min.)

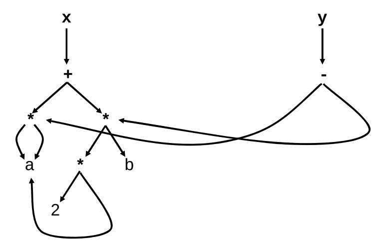
- given the code fragment

```
x := a*a + 2*a*b + b*b;
y := a*a – 2*a*b + b*b;
```

draw the dependency graph before and after common subexpression elimination.

## Answers

dependency graph after CSE



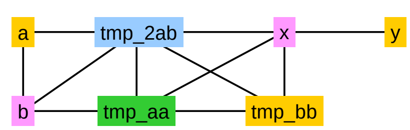

## Exercise (7 min.)

```
{   int tmp_2ab = 2*a*b;
    int tmp_aa = a*a;
    int tmp_bb = b*b;

    x := tmp_aa + tmp_2ab + tmp_bb;
    y := tmp_aa - tmp_2ab + tmp_bb;
}
```

given that a and b are live on entry and dead on exit, and that x and y are live on exit:
(a) construct the register interference graph
(b) color the graph; how many register are needed?

## Answers




4 registers are needed

# Compiler construction in4303 – lecture 10

Imperative & OO languages: context handling

Chapter 6.2

## Exercise (4 min.)

Give the method tables for **`Rectangle`** and **`Square`**

```
abstract class Shape {
   boolean IsShape() {return true;}
   boolean IsRectangle() {return false;}
   boolean IsSquare() {return false;}
   abstract double SurfaceArea();
}
class Rectangle extends Shape {
   double SurfaceArea { ... }
   boolean IsRectangle() {return true;}
}
class Square extends Rectangle {
   boolean IsSquare() {return true;}
}
```

## Answers

Method table for **`Rectangle`**

| |
|---|
| IsShape_Shape_Shape |
| IsRectangle_Shape_Rectangle |
| IsSquare_Shape_Shape |
| SurfaceArea_Shape_Rectangle |

Method table for **`Square`**

| |
|---|
| IsShape_Shape_Shape |
| IsRectangle_Shape_Rectangle |
| IsSquare_Shape_Square |
| SurfaceArea_Shape_Rectangle |

## Exercise (4 min.)

- given an object **e** of class **E**, give the compiled code for the calls
  - `e.m1()`
  - `e.m3()`
  - `e.m4()`

## Answers

| | |
|---|---|
| `e.m1()` | `(*(e->dispatch_table[0]))((Class_C *) e)` |
| `e.m3()` | `(*(e->dispatch_table[2]))( (class_D *)((char *)e + sizeof(Class_C)))` |
| `e.m4()` | `(*(e->dispatch_table[3]))( (class_D *)((char *)e + sizeof(Class_C)))` |

# Compiler construction in4303 – lecture 11

Imperative & OO languages: routines & control flow

Chapter 6.3 - 6.4

## Exercise (5 min.)

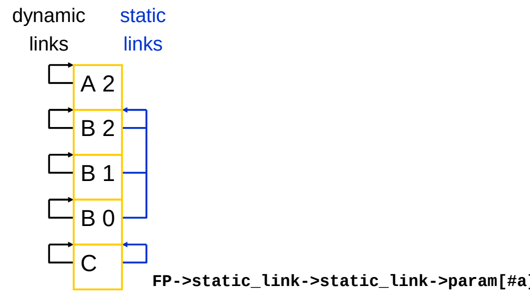
- Given the GNU C routine:

```
void A(int a) {
   void B(int b) {
      void C(void) {
         printf("C called, a = %d\n", a);
      }
      if (b == 0) C() else B(b-1);
   }
   B(a);
}
```

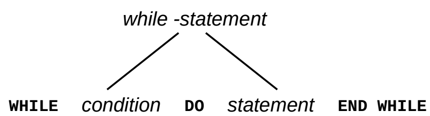
a) draw the stack that results from the call A(2)

b) how does C access the parameter (a) from A?

## Answers

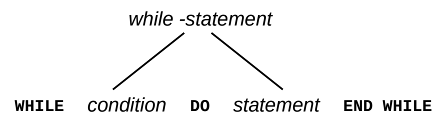



## Exercise (3 min.)




- give a translation schema for while statements

## Answers




```
 GOTO test_label;
loop_label:
 Code statement( statement)
test_label:
 Boolean control code( condition, loop_label , No_label)
```

## Compiler construction in4303 – lecture 12

Memory Management

Chapter 5

## Exercise (5 min.)

- give the pseudo code for free() when using free lists indexed by size.

## Answers

```
PROCEDURE Free (Block pointer):
  SET Chunk pointer TO Block pointer – Admin size;
  SET Index TO 2log(Chunk pointer .size);

  IF Index <= 10:
    SET Chunk pointer .next TO Free list[Index];
    SET Free list[Index] TO Chunk pointer;
  ELSE
    SET Chunk pointer .free TO True;
    // Coalesce subsequent free chunks
```

## Compiler construction in4303 – lecture 13

Functional programming

Chapter 7

## Exercise (5 min.)

- infer the polymorphic type of the following higher-order function:

```
filter f []     = []
filter f (x:xs) = if not(f x) then  filter f xs
                  else x : (filter f xs)
```

## Answers

```
filter f []     = []
filter f (x:xs) = if not(f x) then  filter f xs
                  else x : (filter f xs)
```

filter :: $t_1$ -> $t_2$ -> $t_3$

```
filter f []     = []
```

filter :: $t_1$ -> [a] -> [b]

```
filter f (x:xs) = if not(f x) then  filter f xs
                  else x : (filter f xs)
```

```
    x :: a
    f :: a -> Bool
filter :: (a -> Bool) -> [a] -> [a]
```

## Exercise (6 min.)

- infer the strict arguments of the following recursive function:

```
g x y 0 = x
g x y z = g y x (z-1)
```

- how many iterations are needed?

## Answers

```
g x y 0 = x
g x y z = g y x (z-1)
```

```
g x y z = if z == 0 then x
          else g y x (z-1)
```

| step | assumption | result |
|---|---|---|
| 1 | {x,y,z} | {x,z} |
| 2 | {x,z} | {z} |
| 3 | {z} | {z} |
| 4 | | |

## Compiler construction
## in4303 – lecture 14

Logic programs

Chapter 8

## Exercise (5 min.)

Specify Prolog rules for the binary relations
- `offspring` (nakomeling)
- `spouse` (echtgenoot)

using the `parent` relation.

```
parent(dick,koen).
parent(lia,koen).

parent(koen,allard).
parent(koen,linde).
parent(koen,merel).
```

**The bait hides the hook**

## Answers

```
offspring(X,Y) :- parent(X,Y).
offspring(X,Y) :- parent(X,Z), offspring(Z,Y).
```

```
spouse(X,Y) :- parent(X,Z), parent(Y,Z),
               X \= Y, !.
```

`X \= Y` to rule out `spouse(koen,koen)`

`!` to rule out duplicates (multiple children)