Compilerbau

Stephan Schulz

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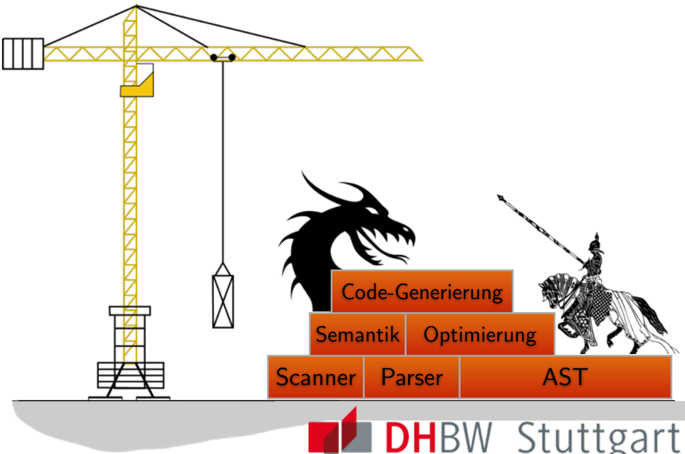

DHBW Stuttgart
Duale Hochschule
Baden-Württemberg

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- Stephan Schulz
  - Dipl.-Inform., U. Kaiserslautern, 1995
  - Dr. rer. nat., TU München, 2000
  - Visiting professor, U. Miami, 2002
  - Visiting professor, U. West Indies, 2005
  - Visiting lecturer (Hildesheim, Offenburg, ...) seit 2009
  - Industry experience: Building Air Traffic Control systems
    - System engineer, 2005
    - Project manager, 2007
    - Product Manager, 2013
  - Professor, DHBW Stuttgart, 2014

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Research: Logic & Deduction

Goals for Today

- Practical issues
- Programming language survey
- Execution of languages
- Low-level code vs. high-level code
- Structure of a Compiler
- Refresher
  - Grammars
  - Flex/Bison
- Programming exercises
  - Scientific calculator revisited

This Course in Context

- *Formal languages and automata*
  - Basic theory - languages and automata
  - General grammars
  - Abstract parsing
  - Computability

Focus on foundations

- *Compiler construction*
  - Advanced theory - parsers and languages
  - Tools and their use
  - Writing parsers and scanners
  - Code generation and run times

Focus on practical applications

Practical issues

- Lecture time: Wednesdays, 12:30-16:45
  - Lecture (with exercises): 12:30-14:45
  - Lab: 15:00-16:45
  - Breaks will be somewhat flexible
  - No lecture on March 25th (I'm snowboarding)
- Grading:
  - Lecture *Compilerbau*: Written Exam, grade averaged with *Formal Languages&Automata* for module grade
  - Lab: Pass/Fail based on success in exercises

Computing Environment

- For practical exercises, you will need a complete Linux/UNIX environment. If you do not run one natively, there are several options:
  - You can install VirtualBox (`https://www.virtualbox.org`) and then install e.g. Ubuntu (`http://www.ubuntu.com/`) on a virtual machine. Make sure to install the *Guest Additions*
  - For Windows, you can install the complete UNIX emulation package Cygwin from `http://cygwin.com`
  - For MacOS, you can install `fink` (`http://fink.sourceforge.net/`) or MacPorts (`https://www.macports.org/`) and the necessary tools
- You will need at least `flex`, `bison`, `gcc`, `grep`, `sed`, `AWK`, `make`, and a good text editor

Resources

- Course web page
  - `http://wwwlehre.dhbw-stuttgart.de/~sschulz/cb2015.html`
- Literature
  - Alfred V. Aho, Monica S. Lam, Ravi Sethi, Jeffrey D. Ullman: *Compilers: Principles, Techniques, and Tools*
  - Kenneth C. Louden: *Compiler Construction - Principles and Practice*
  - Ulrich Hedtstück: *Einführung in die theoretische Informatik*

Exercise: Programming Languages

- Name and describe several modern programming languages!

Modern Programming Languages

Desirable properties of high-level languages

- Expressive and flexible
  - Close to application domains
  - Good abstractions
  - Powerful constructs
  - Readable
- Compact
  - Programmer productivity depends on length (!)
- Machine independent
  - Code should run on many platforms
  - Code should run on evolving platforms
- Strong error-checking
  - Static
  - Dynamic
- Efficiently executable

Low-Level Code

- Machine code
  - Binary
  - Machine-specific
  - Operations (and operands) encoded in instruction words
  - Basic operations only
  - Manipulates finite number of registers
  - Direct access to memory locations
  - Flow control via conditional and unconditional jumps (think `goto`)
  - Basic data types (bytes, words)

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Directly executable by processor

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Directly executable by processor

- Assembly languages
  - Textual representation of machine code
  - Symbolic names for operations and operands
  - Labels for addresses (code and data)

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Directly executable by processor

- Assembly languages
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Direct one-to-one mapping to machine code

Exercise: Low-Level Code – Minimal C

- Predefined global variables
  - Integers `R0, R1, R2, R3, R4`
  - Integer array `mem[MAXMEM]`
  - No new variables allowed
- No parameters (or return) for functions
- Flow control: Only `if` and `goto` (not `while`, `for`, ...)
  - No blocks after `if` (only one command allowed)
- Arithmetic only between `R0, R1, R2, R3, R4`
  - Result must be stored in one of `R0, R1, R2, R3, R4`
  - Operands: Only `R0, R1, R2, R3, R4` allowed (no nested sub-expressions)
  - Unary incement/decrement is ok (`R0++`)
  - `R0, R1, R2, R3, R4` can be stored in/loaded from `mem`, indexed with a fixed address or one of the variables.

Exercise: Minimal C Example

```
/* Compute sum from 0 to R0, return result in R1 */

void user_code(void)
{
    /* R0 is the input value and limit */
    R1 = 0;    /* Sum, value returned */
    R2 = 0;    /* Loop counter */
    R3 = 1;    /* For increments */

loop:
    if(R2 > R0)
        goto end;
    R1 = R1+R2;
    R2 = R2+R3;
    goto loop;
end:
    return;
}
```

Exercise: Low-Level Code

- Write (in Minimal C) the following functions:
  - A program computing the factorial of `R0`
  - A program computing the Fibonacci-number of `R0` iteratively
  - A program computing the Fibonacci-number of `R0` recursively
- You can find a frame for your code at the course web page,
  `http://wwwlehre.dhbw-stuttgart.de/~sschulz/cb2015.html`

Surprise!

Computers don't execute high-level languages (directly)!

Execution of high-level programs

Compiled languages

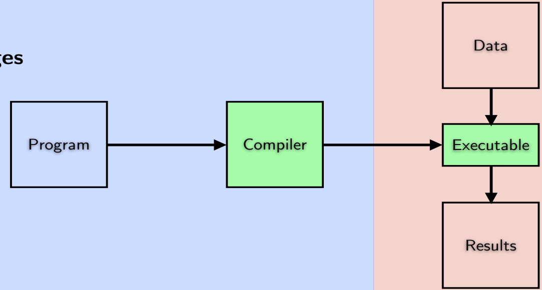
Interpreted languages

Development Time

Run Time

Execution of high-level programs

Compiled languages

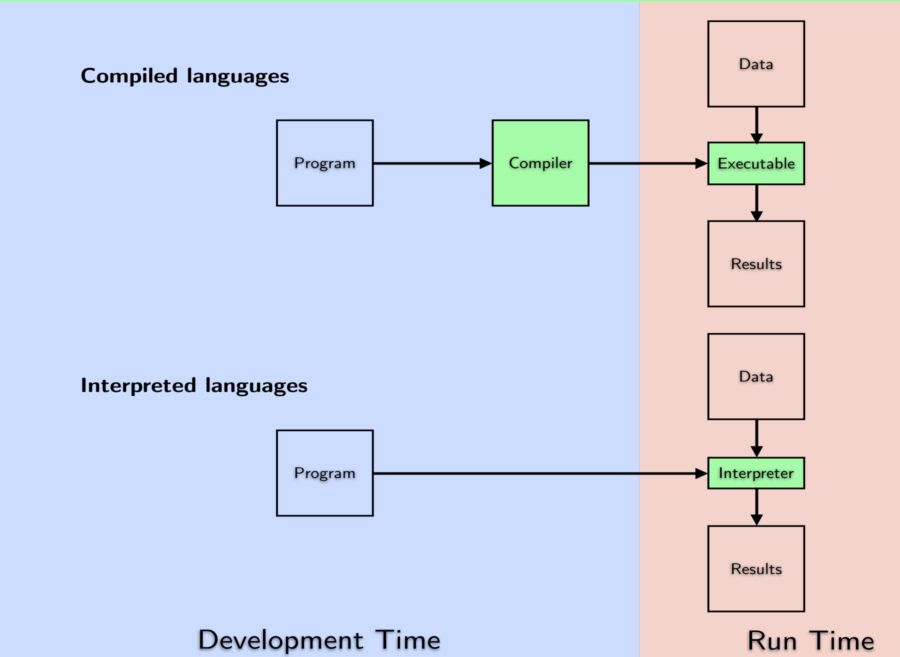


Interpreted languages

Development Time

Run Time

Execution of high-level programs



Compilers

Compilers translate high-level languages into low-level code!

Reminder: Syntactic Structure of Computer Languages

- Most computer languages are mostly context-free
  - Regular: vocabulary
    - Keywords, operators, identifiers
    - Described by regular expressions or regular grammar
    - Handled by (generated or hand-written) scanner/tokenizer/lexer
  - Context-free: program structure
    - Matching parenthesis, block structure, algebraic expressions, ...
    - Described by context-free grammar
    - Handled by (generated or hand-written) *parser*
  - Context-sensitive: e.g. declarations
    - Described by human-readable constraints
    - Handled in an ad-hoc fashion (e.g. symbol table)

High-Level Architecture of a Compiler

Source handler

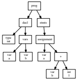
↓ Sequence of characters:
i,n,t, ␣, a,,, b, ;, a, =, b, +, 1, ;

Lexical analysis (tokeniser)

↓ Sequence of tokens:
(id, “int”), (id, “a”), (id, “b”), (semicolon), (id, “a”), (eq), (id, “b”), (plus), (int, “1”), (semicolon)

Syntactic analysis (parser)

↓ e.g. Abstract syntax tree



Semantic analysis

↓ e.g. AST+symbol table

Variable	Type
a	int
b	int

Code generation (several optimisation passes)

↓ e.g. assembler code

```
ld a,b
ld c, 1
add c
...
```

Source Handler

- Handles input files
- Provides character-by-character access
- May maintain file/line/colum (for error messages)
- May provide look-ahead

Result: Sequence of characters (with positions)

Lexical Analysis/Scanning

- Breaks program into token
- Typical tokens:
  - Reserved word (`if`, `while`)
  - Identifier (`i`, `database`)
  - Symbols (`{`, `}`, `(`, `)`, `+`, `-`, `...`

Result: Sequence of tokens

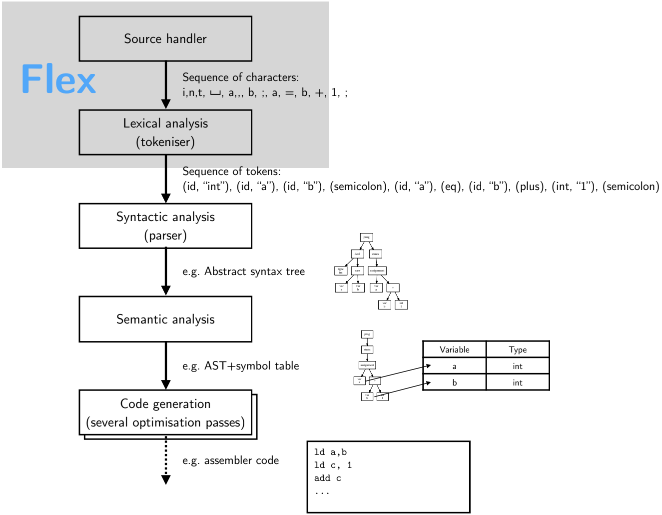
Exercise: Lexical Analysis

```
int main(int argc, char* argv[])
{
    R0 = 0;
    R1 = 0;
    R2 = 0;
    R3 = 1;
    R4 = 1;
    for(int i = 0; i<MAXMEM; i++)
    {
        mem[i] = 0;
    }

    user_code();

    return 0;
}
```

Automatisation with Flex

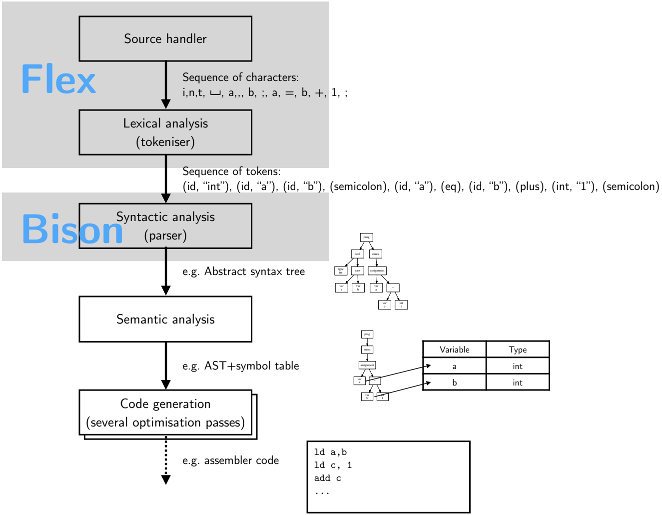


Syntactical Analysis/Parsing

- Description of the language with a context-free grammar
- Parsing:
  - Try to build a *parse tree*/abstract syntax tree (AST)
  - Parse tree unambiguously describes structure of a program
  - AST reflects abstract syntax (can e.g. drop parenthesis)
- Methods:
  - Manual recursive descent parser
  - Automatic with a table-driven bottom-up parser

Result: Abstract Syntax Tree

Automatisation with Bison



Semantic Analysis

- Analyze static properties of the program
  - Which variable has which type?
  - Are all expressions well-typed?
  - Which names are defined?
  - Which names are referenced?
- Core tool: Symbol table

Result: Annotated AST

Optimization

- Transform Abstract Syntax Tree to generate better code
  - Smaller
  - Faster
  - Both
- Mechanisms
  - Common sub-expression elimination
  - Loop unrolling
  - Dead code/data elimination
  - ...

Result: Optimized AST

Code Generation

- Convert optimized AST into low-level code
- Target languages:
  - Assembly code
  - Machine code
  - VM code (z.B. JAVA byte-code, p-Code)
  - C (as a "portable assembler")
  - ...

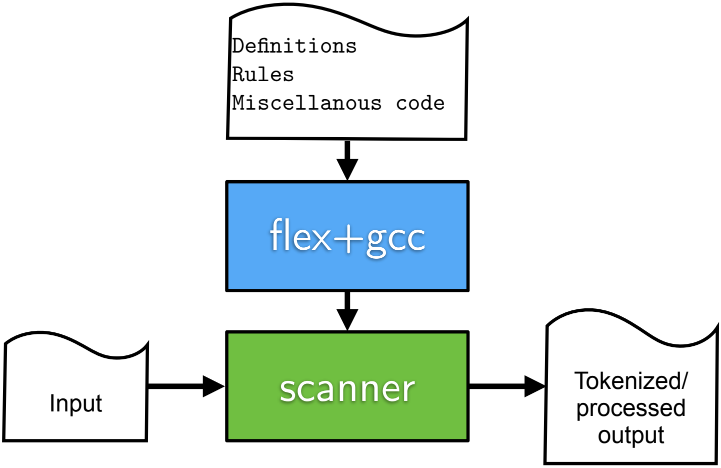
Result: Program in target language

Refresher: Flex

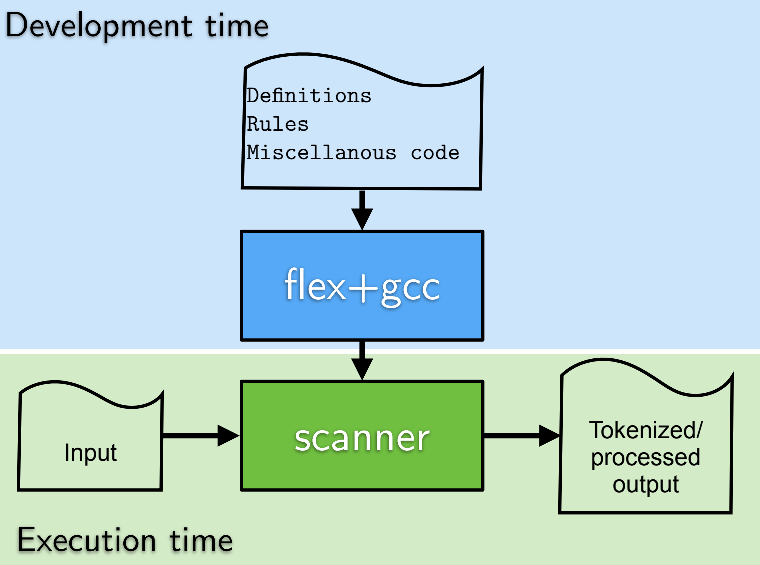
Flex Overview

- Flex is a scanner generator
- Input: Specification of a regular language and what to do with it
  - Definitions - named regular expressions
  - Rules - patters+actions
  - (miscellaneous support code)
- Output: Source code of scanner
  - Scans input for patterns
  - Executes associated actions
  - Default action: Copy input to output
  - Interface for higher-level processing: `yylex()` function

Flex Overview



Flex Overview



Flex Example Task

- (Artificial) goal: Sum up all numbers in a file, separately for ints and floats
- Given: A file with numbers and commands
  - Ints: Non-empty sequences of digits
  - Floats: Non-empty sequences of digits, followed by decimal dot, followed by (potentially empty) sequence of digits
  - Command `print`: Print current sums
  - Command `reset`: Reset sums to 0.
- At end of file, print sums

Flex Example Output

Input

```
12 3.1415
0.33333
print reset
2 11
1.5 2.5 print
1
print 1.0
```

Output

```
int:   12 ("12")
float: 3.141500 ("3.1415")
float: 0.333330 ("0.33333")
Current: 12 : 3.474830
Reset
int:   2 ("2")
int:   11 ("11")
float: 1.500000 ("1.5")
float: 2.500000 ("2.5")
Current: 13 : 4.000000
int:   1 ("1")
Current: 14 : 4.000000
float: 1.000000 ("1.0")
Final  14 : 5.000000
```

Basic Structure of Flex Files

- Flex files have 3 sections
  - Definitions
  - Rules
  - User Code
- Sections are separated by %%
- Flex files traditionally use the suffix `.l`

Example Code (definition section)

```
%%option noyywrap

DIGIT    [0-9]

%{
   int    intval   = 0;
   double floatval = 0.0;
%}

%%
```

Example Code (rule section)

```
{DIGIT}+    {
               printf( "int:   %d (\"%s\")\n", atoi(yytext), yytext );
               intval += atoi(yytext);
            }
{DIGIT}+"."{DIGIT}*        {
            printf( "float: %f (\"%s\")\n", atof(yytext),yytext );
            floatval += atof(yytext);
            }
reset {
        intval = 0;
        floatval = 0;
        printf("Reset\n");
      }
print {
         printf("Current: %d : %f\n", intval, floatval);
      }
\n|. {
        /* Skip */
      }
```

Example Code (user code section)

```
%%
int main( int argc, char **argv )
{
   ++argv, --argc;  /* skip over program name */
   if ( argc > 0 )
      yyin = fopen( argv[0], "r" );
   else
      yyin = stdin;

   yylex();

   printf("Final  %d : %f\n", intval, floatval);
}
```

Generating a scanner

```
> flex  -t numbers.l > numbers.c
> gcc   -c -o numbers.o numbers.c
> gcc numbers.o -o scan_numbers
> ./scan_numbers Numbers.txt
int:   12 ("12")
float: 3.141500 ("3.1415")
float: 0.333330 ("0.33333")
Current: 12 : 3.474830
Reset
int:   2 ("2")
int:   11 ("11")
float: 1.500000 ("1.5")
float: 2.500000 ("2.5")
...
```

Flexing in detail

```
> flex -tv numbers.l > numbers.c
  scanner options: -tvI8 -Cem
  37/2000 NFA states
  18/1000 DFA states (50 words)
  5 rules
  Compressed tables always back-up
  1/40 start conditions
  20 epsilon states, 11 double epsilon states
  6/100 character classes needed 31/500 words
        of storage, 0 reused
  36 state/nextstate pairs created
  24/12 unique/duplicate transitions
  ...
  381 total table entries needed
```

Definition Section

- Can contain `flex` options
- Can contain (C) initialization code
  - Typically `#include()` directives
  - Global variable definitions
  - Macros and type definitions
  - Initialization code is embedded in %{ and %}
- Can contain definitions of regular expressions
  - Format: `NAME RE`
  - Defined NAMES can be referenced later

Example Code (definition section) (revisited)

```
%%option noyywrap

DIGIT    [0-9]

%{
   int    intval   = 0;
   double floatval = 0.0;
%}


%%
```

Rule Section

- This is the core of the scanner!
- Rules have the form `PATTERN ACTION`
- Patterns are regular expressions
  - Typically use previous definitions
- THERE IS WHITE SPACE BETWEEN PATTERN AND ACTION!
- Actions are C code
  - Can be embedded in { and }
  - Can be simple C statements
  - For a token-by-token scanner, must include `return` statement
  - Inside the action, the variable `yytext` contains the text matched by the pattern
  - Otherwise: Full input file is processed

Example Code (rule section) (revisited)

```
{DIGIT}+    {
               printf( "int:   %d (\"%s\")\n", atoi(yytext), yytext );
               intval += atoi(yytext);
            }
{DIGIT}+"."{DIGIT}*        {
            printf( "float: %f (\"%s\")\n", atof(yytext),yytext );
            floatval += atof(yytext);
            }
reset {
        intval = 0;
        floatval = 0;
        printf("Reset\n");
      }
print {
         printf("Current: %d : %f\n", intval, floatval);
      }
\n|. {
        /* Skip */
      }
```

User code section

- Can contain all kinds of code
- For stand-alone scanner: must include `main()`
- In `main()`, the function `yylex()` will invoke the scanner
- `yylex()` will read data from the file pointer `yyin` (so `main()` must set it up reasonably

Example Code (user code section) (revisited)

```
%%
int main( int argc, char **argv )
{
   ++argv, --argc;  /* skip over program name */
   if ( argc > 0 )
      yyin = fopen( argv[0], "r" );
   else
      yyin = stdin;

   yylex();

   printf("Final  %d : %f\n", intval, floatval);
}
```

A comment on comments

- Comments in Flex are complicated
  - ... because nearly everything can be a pattern
- Simple rules:
  - Use old-style C comments `/* This is a comment */`
  - Never start them in the first column
  - Comments are copied into the generated code
  - Read the manual if you want the dirty details

Flex Miscellany

- Flex online:
  - http://flex.sourceforge.net/
  - Manual: http://flex.sourceforge.net/manual/
  - REs: http://flex.sourceforge.net/manual/Patterns.html
- make knows flex
  - Make will automatically generate file.o from file.l
  - Be sure to set LEX=flex to enable flex extensions
  - Makefile example:

```
LEX=flex
all: scan_numbers
numbers.o: numbers.l

scan_numbers: numbers.o
        gcc numbers.o -o scan_numbers
```

Refresher: Bison

YACC/Bison

- Yacc - Yet Another Compiler Compiler
  - Originally written ≈1971 by Stephen C. Johnson at AT&T
  - LALR parser generator
  - Translates grammar into syntax analyzer

- GNU Bison
  - Written by Robert Corbett in 1988
  - Yacc-compatibility by Richard Stallman
  - Output languages now C, C++, Java
- Yacc, Bison, BYacc, . . . mostly compatible (POSIX P1003.2)

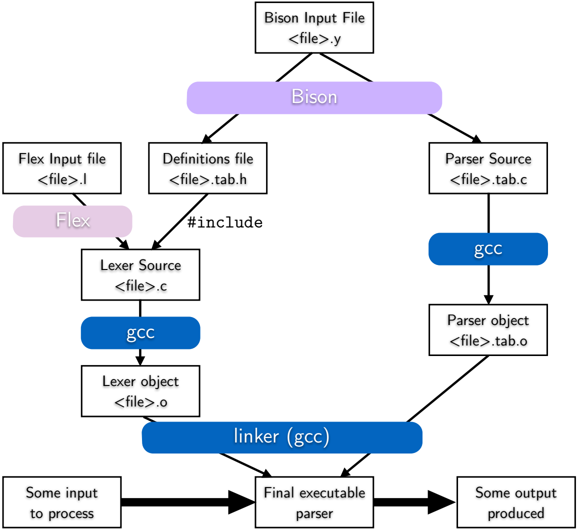
Yacc/Bison Background

- By default, Bison constructs a 1 token Look-Ahead Left-to-right Rightmost-derivation or LALR(1) parser
  - Input tokens are processed left-to-right
  - Shift-reduce parser:
    - Stack holds tokens (terminals) and non-terminals
    - Tokens are shifted from input to stack. If the top of the stack contains symbols that represent the right hand side (RHS) of a grammar rule, the content is reduced to the LHS
    - Since input is reduced left-to-right, this corresponds to a rightmost derivation
    - Ambiguities are solved via look-ahead and special rules
    - If input can be reduced to start symbol, success!
    - Error otherwise
- LALR(1) is efficient in time and memory
  - Can parse "all reasonable languages"
  - For unreasonable languages, Bison (but not Yacc) can also construct GLR (General LR) parsers
    - Try all possibilities with back-tracking
    - Corresponds to the *non-determinism* of stack machines

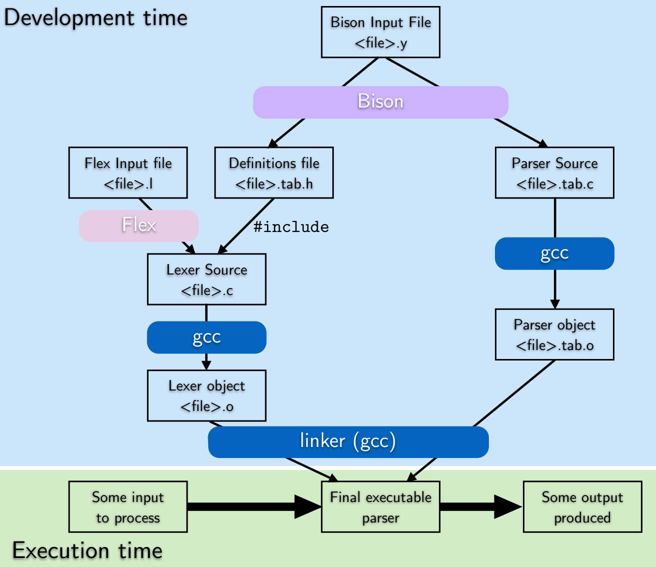
Yacc/Bison Overview

- Bison reads a specification file and converts it into (C) code of a parser
- Specification file: Definitions, grammar rules with actions, support code
  - Definitions: Token names, associated values, includes, declarations
  - Grammar rules: Non-terminal with alternatives, action associated with each alternative
  - Support code: e.g. `main()` function, error handling...
  - Syntax similar to (F)lex
    - Sections separated by %%
    - Special commands start with %
- Bison generates function `yyparse()`
- Bison needs function `yylex()`
  - Usually provided via (F)lex

Yacc/Bison workflow



Yacc/Bison workflow



Example task: Desk calculator

- Desk calculator
  - Reads algebraic expressions and assignments
  - Prints result of expressions
  - Can store values in registers `R0-R99`

Example task: Desk calculator

- Desk calculator
  - Reads algebraic expressions and assignments
  - Prints result of expressions
  - Can store values in registers `R0-R99`
- Example session:

```
[Shell] ./scicalc
R10=3*(5+4)
> RegVal: 27.000000
(3.1415*R10+3)
> 87.820500
R9=(3.1415*R10+3)
> RegVal: 87.820500
R9+R10
> 114.820500
...
```

Abstract grammar for desk calculator (partial)

$G_{DC} = \langle V_N, V_T, P, S \rangle$

- $V_T = \{$`PLUS`, `MULT`, `ASSIGN`, `OPENPAR`, `CLOSEPAR`, `REGISTER`, `FLOAT`, $\ldots\}$
  - Some terminals are single characters (+, =, ...)
  - Others are complex: `R10`, `1.3e7`
  - Terminals ("tokens") are generated by the lexer
- $V_N = \{$`stmt`, `assign`, `expr`, `term`, `factor`, $\ldots\}$

- P :

```
stmt     →  assign
          |  expr
assign   →  REGISTER ASSIGN expr
expr     →  expr PLUS term
          |  term
term     →  term MULT factor
          |  factor
factor   →  REGISTER
          |  FLOAT
          |  OPENPAR expr CLOSEPAR
```

- $S =$ *handwave*
  - For a single statement, $S =$ `stmt`
  - In practice, we need to handle sequences of statements and empty input lines (not reflected in the grammar)

Lexer interface

- Bison parser requires `yylex()` function
- `yylex()` returns token
  - Token text is defined by regular expression pattern
  - Tokens are encoded as integers
  - Symbolic names for tokens are defined by Bison in generated header file
    - By convention: Token names are all `CAPITALS`
- `yylex()` provides optional semantic value of token
  - Stored in global variable `yylval`
  - Type of `yylval` defined by Bison in generated header file
    - Default is `int`
    - For more complex situations often a `union`
    - For our example: Union of double (for floating point values) and integer (for register numbers)

Lexer for desk calculator (1)

```
/*
     Lexer for a minimal "scientific" calculator.

     Copyright 2014 by Stephan Schulz, schulz@eprover.org.

     This code is released under the GNU General Public Licence
     Version 2.
 */

%option noyywrap

%{
   #include "scicalcparse.tab.h"
%}
```

Lexer for desk calculator (2)

```
DIGIT       [0-9]
INT         {DIGIT}+
PLAINFLOAT {INT}|{INT}[.]|{INT}[.]{INT}|[.]{INT}
EXP         [eE](\+|-)?{INT}
NUMBER      {PLAINFLOAT}{EXP}?
REG         R{DIGIT}{DIGIT}?

%%

"*" {return MULT;}
"+" {return PLUS;}
"=" {return ASSIGN;}
"(" {return OPENPAR;}
")" {return CLOSEPAR;}
\n  {return NEWLINE;}
```

Lexer for desk calculator (3)

```
{REG}    {
           yylval.regno = atoi(yytext+1);
           return REGISTER;
         }

{NUMBER} {
           yylval.val = atof(yytext);
           return FLOAT;
        }

[ ] { /* Skip  whitespace*/ }

 /* Everything else is an invalid character. */
.    { return ERROR;}

%%
```

Data model of desk calculator

- Desk calculator has simple state
  - 100 floating point registers
  - `R0-R99`
- Represented in C as array of doubles:

```
#define MAXREGS 100

double regfile[MAXREGS];
```

- Needs to be initialized in support code!

Bison code for desk calculator: Header

```
%{
   #include <stdio.h>

   #define MAXREGS 100

   double regfile[MAXREGS];

   extern int yyerror(char* err);
   extern int yylex(void);
%}

%union {
   double val;
   int    regno;
}
```

Bison code for desk calculator: Tokens

```
%start stmtseq

%left  PLUS
%left  MULT
%token ASSIGN
%token OPENPAR
%token CLOSEPAR
%token NEWLINE
%token REGISTER
%token FLOAT
%token ERROR

%%
```

Actions in Bison

- Bison is based on syntax rules with associated actions
  - Whenever a reduce is performed, the action associated with the rule is executed
- Actions can be arbitrary C code
- Frequent: semantic actions
  - The action sets a semantic value based on the semantic value of the symbols reduced by the rule
  - For terminal symbols: Semantic value is `yylval` from Flex
  - Semantic actions have "historically valuable" syntax
    - Value of reduced symbol: `$$`
    - Value of first symbol in syntax rule body: `$1`
    - Value of second symbol in syntax rule body: `$2`
    - ...
    - Access to named components: `$<val>1`

Bison code for desk calculator: Grammar (1)

```
stmtseq: /* Empty */
    | NEWLINE stmtseq       {}
    | stmt  NEWLINE stmtseq {}
    | error NEWLINE stmtseq {};  /* After an error,
                                    start afresh */
```

- Head: sequence of statements
- First body line: Skip empty lines
- Second body line: separate current statement from rest
- Third body line: After parse error, start again with new line

Bison code for desk calculator: Grammar (2)

```
stmt: assign  {printf("> RegVal: %f\n", $<val>1);}
     |expr    {printf("> %f\n", $<val>1);};

assign: REGISTER ASSIGN expr {regfile[$<regno>1] = $<val>3;
                              $<val>$ = $<val>3;} ;

expr: expr PLUS term {$<val>$ = $<val>1 + $<val>3;}
    | term {$<val>$ =  $<val>1;};

term: term MULT factor {$<val>$ = $<val>1 * $<val>3;}
    | factor {$<val>$ =  $<val>1;};

factor: REGISTER {$<val>$ = regfile[$<regno>1];}
      | FLOAT  {$<val>$ =  $<val>1;}
      | OPENPAR expr CLOSEPAR {$<val>$ =  $<val>2;};
```

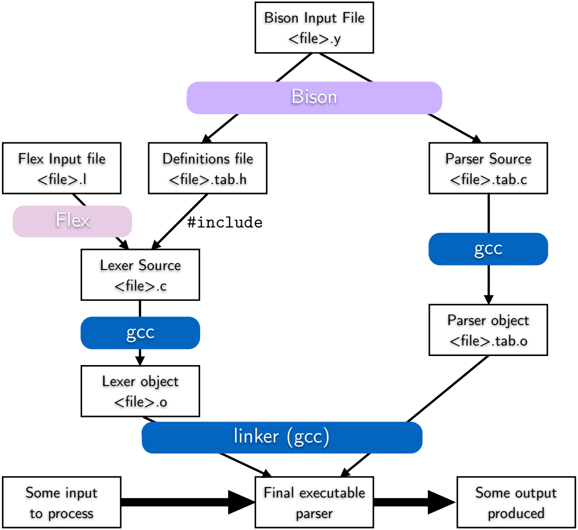
Bison code for desk calculator: Support code

```
int yyerror(char* err)
{
   printf("Error: %s\n", err);
   return 0;
}

int main (int argc, char* argv[])
{
  int i;

  for(i=0; i<MAXREGS; i++)
  {
     regfile[i] = 0.0;
  }
  return yyparse();
}
```

Reminder: Workflow and dependencies



Building the calculator

1. Generate parser C code and include file for lexer
   - `bison -d scicalcparse.y`
   - Generates `scicalcparse.tab.c` and `scicalcparse.tab.h`
2. Generate lexer C code
   - `flex -t scicalclex.l > scicalclex.c`
3. Compile lexer
   - `gcc -c -o scicalclex.o scicalclex.c`
4. Compile parser and support code
   - `gcc -c -o scicalcparse.tab.o scicalcparse.tab.c`
5. Link everything
   - `gcc scicalclex.o scicalcparse.tab.o -o scicalc`
6. Fun!
   - `./scicalc`

Exercise

- Exercise 1 (Refresher):
  - Go to `http://wwwlehre.dhbw-stuttgart.de/~sschulz/cb2015.html`
  - Download `scicalcparse.y` and `scicalclex.l`
  - Build the calculator
  - Run and test the calculator
- Exercise 2 (Warm-up):
  - Add support for division and subtraction `/`, `-`
  - Add support for unary minus (the negation operator `-`)
- Exercise 3 (Bonus):
  - Change the desk calculator so that it converts its input into a C program that will perform the same actions that the calculator performed interactively!

Review: Goals for Today

- Practical issues
- Programming language survey
- Execution of languages
- Low-level code vs. high-level code
- Structure of a Compiler
- Refresher
  - Grammars
  - Flex/Bison
- Programming exercises
  - Scientific calculator revisited

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Refresher
- Reminder: Grammars and Chomsky-Hierarchy
  - Grammars
  - Regular languages and expressions
  - Context-free grammars and languages
- Syntactic structure of programming languages
- *nanoLang*
- Programming exercise: Tokenizing *nanoLang*

Refresher

- Some properties of programming languages and implementations
  - Object oriented vs. Procedural
  - Imperative vs. Functional
  - Statically typed vs. dynamically typed (vs. „no types“)
  - Compiled vs. interpreted
- High-level level languages
  - Expressive/Complex functionality
  - Features correspond to application concepts
  - Good abstraction
- Low-level languages
  - Simple operations
  - Features dictated by hardware architecture
  - (Close to) what processors can execute
  - Limited abstraction

Refresher

- Structure of compiler
  - Tokenizer
  - Parser
  - Semantic analyis
  - Optimizer
  - Code generator
  - ...
- Some applications of compiler technology
  - Implementation of programming languages
  - Parsing of data formats/serialization
    - E.g. Word documents - may include optimization!
    - HTML/XML for web pages/SOA
    - XSLT document transformers
    - $\LaTeX$
    - ATCCL
    - ...
- Flex & Bison

Refresher: Grammars

Formal Grammars: Motivation

Formal grammars describe formal languages!

- Derviative approach
  - A grammar has a set of rules
  - Rules replace words with words
  - A word that can be derived from a special start symbol is in the language of the grammar

Formal Grammars: Motivation

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- Derviative approach
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  - A word that can be derived from a special start symbol is in the language of the grammar

In the concrete case of programming languages, "Words of the language" are syntactically correct programs!

Grammars: Examples

$$S \to aA, \quad A \to bB, \quad B \to \varepsilon$$

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$S \to aA, \quad A \to bB, \quad B \to \varepsilon$
generates ab (starting from S): $S \to aA \to abB \to ab$

Grammars: Examples

$S \rightarrow aA, \quad A \rightarrow bB, \quad B \rightarrow \varepsilon$
generates ab (starting from S): $S \rightarrow aA \rightarrow abB \rightarrow ab$

$S \rightarrow \varepsilon, \quad S \rightarrow aSb$

Grammars: Examples

$S \to aA, \quad A \to bB, \quad B \to \varepsilon$
generates ab (starting from S): $S \to aA \to abB \to ab$

$S \to \varepsilon, \quad S \to aSb$
generates $a^n b^n$

Grammars: definition

Noam Chomsky defined a grammar as a quadruple

$$G = \langle V_N, V_T, P, S \rangle \tag{1}$$

with

1. the set of non-terminal symbols V_N,
2. the set of terminal symbols V_T,
3. the set of production rules P of the form

$$\alpha \rightarrow \beta \tag{2}$$

$$\text{with} \quad \alpha \in V^* V_N V^*, \beta \in V^*, V = V_N \cup V_T$$

4. the distinguished start symbol $S \in V_N$.

Grammars: Shorthand

For the sake of simplicity, we will be using the short form

$$\alpha \to \beta_1 | \cdots | \beta_n \quad \text{replacing} \quad \begin{array}{l} \alpha \to \beta_1 \\ \vdots \\ \alpha \to \beta_n \end{array} \tag{3}$$

Example: C identifiers

We want to define a grammar

$$G = \langle V_N, V_T, P, S \rangle \tag{4}$$

to describe identifiers of the `C` programming language:

- alpha-numeric words
- which must not start with a digit
- and may contain an underscore (_)

Example: C identifiers

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$$G = \langle V_N, V_T, P, S \rangle \tag{4}$$

to describe identifiers of the C programming language:

- alpha-numeric words
- which must not start with a digit
- and may contain an underscore (_)

$$
\begin{aligned}
V_N &= \{I, R, L, D\} \text{ (identifier, rest, letter, digit)},\\
V_T &= \{\mathtt{a}, \cdots, \mathtt{z}, \mathtt{A}, \cdots, \mathtt{Z}, \mathtt{0}, \cdots, \mathtt{9}, \_\},\\
P &= \{ \quad \begin{array}{rcl}
I & \rightarrow & LR|\_R|L|\_ \\
R & \rightarrow & LR|DR|\_R|L|D|\_ \\
L & \rightarrow & \mathtt{a}|\cdots|\mathtt{z}|\mathtt{A}|\cdots|\mathtt{Z} \\
D & \rightarrow & \mathtt{0}|\cdots|\mathtt{9}\}
\end{array}\\
S &= I.
\end{aligned}
$$

Formal grammars: derivation

Derivation: description of operation of grammars
Given the grammar

$$G = \langle V_N, V_T, P, S \rangle, \tag{5}$$

we define the relation

$$x \Rightarrow_G y \tag{6}$$

$$\text{iff } \exists u, v, p, q \in V^* : (x = upv) \wedge (p \to q \in P) \wedge (y = uqv) \tag{7}$$

pronounced as "G derives y from x in one step".

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pronounced as "G derives y from x in one step".

We also define the relation

$$x \Rightarrow_G^* y \text{ iff } \exists w_0, \ldots, w_n \tag{8}$$

$$\text{with } w_0 = x, w_n = y, w_{i-1} \Rightarrow_G w_i \text{ for } i \in \{1, \cdots, n\}$$

pronounced as "G derives y from x (in zero or more steps)".

Formal grammars: derivation example I

$$G = \langle V_N, V_T, P, S \rangle \tag{9}$$

with

1. $V_N = \{S\}$,
2. $V_T = \{\mathtt{0}\}$,
3. $P = \{S \rightarrow \mathtt{0}S, \quad S \rightarrow \mathtt{0}\}$,
4. $S = S$.

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Derivations of G have the general form

$$S \Rightarrow 0S \Rightarrow 00S \Rightarrow \cdots \Rightarrow 0^{n-1}S \Rightarrow 0^n \tag{10}$$

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Derivations of G have the general form

$$S \Rightarrow 0S \Rightarrow 00S \Rightarrow \cdots \Rightarrow 0^{n-1}S \Rightarrow 0^n \tag{10}$$

Apparently, the language produced by G (or the language of G) is

$$L(G) = \{0^n | n \in \mathbb{N}; n > 0\}. \tag{11}$$

Formal grammars: derivation example II

$$G = \langle V_N, V_T, P, S \rangle \tag{12}$$

with

1. $V_N = \{S\}$,
2. $V_T = \{\mathtt{0}, \mathtt{1}\}$,
3. $P = \{S \to \mathtt{0}S\mathtt{1}, \quad S \to \mathtt{01}\}$,
4. $S = S$.

Formal grammars: derivation example II

$$G = \langle V_N, V_T, P, S \rangle \tag{12}$$

with

1. $V_N = \{S\}$,
2. $V_T = \{0, 1\}$,
3. $P = \{S \to 0S1, \quad S \to 01\}$,
4. $S = S$.

Derivations of G have the general form

$$S \Rightarrow 0S1 \Rightarrow 00S11 \Rightarrow \cdots \Rightarrow 0^{n-1}S1^{n-1} \Rightarrow 0^n 1^n. \tag{13}$$

Formal grammars: derivation example II

$$G = \langle V_N, V_T, P, S \rangle \tag{12}$$

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Derivations of G have the general form

$$S \Rightarrow \mathtt{0}S\mathtt{1} \Rightarrow \mathtt{00}S\mathtt{11} \Rightarrow \cdots \Rightarrow \mathtt{0}^{n-1}S\mathtt{1}^{n-1} \Rightarrow \mathtt{0}^n\mathtt{1}^n. \tag{13}$$

The language of G is

$$L(G) = \{\mathtt{0}^n\mathtt{1}^n | n \in \mathbb{N}; n > 0\}. \tag{14}$$

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The language of G is

$$L(G) = \{0^n1^n | n \in \mathbb{N}; n > 0\}. \tag{14}$$

Reminder: L(G) is not regular!

The Chomsky hierarchy (0)

Given the grammar

$$G = \langle V_N, V_T, P, S \rangle, \qquad (15)$$

we define the following grammar/language classes

- G is of Type 0 or *unrestricted*

The Chomsky hierarchy (0)

Given the grammar

$$G = \langle V_N, V_T, P, S \rangle, \tag{15}$$

we define the following grammar/language classes

- G is of Type 0 or *unrestricted*

All grammars are Type 0!

The Chomsky hierarchy (1)

$$G = \langle V_N, V_T, P, S \rangle, \tag{16}$$

- G is Type 1 or *context-sensitive*
  if all productions are of the form

$$\alpha_1 A \alpha_2 \to \alpha_1 \beta \alpha_2 \text{ with } A \in V_N; \alpha_1, \alpha_2 \in V^*, \beta \in VV^* \tag{17}$$

  Exception:

$$S \to \varepsilon \in P \text{ is allowed if}$$

$$\alpha_1, \alpha_2 \in (V \backslash \{S\})^* \text{ and } \beta \in (V \backslash \{S\})(V \backslash \{S\})^* \tag{18}$$

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  - If $S \rightarrow \varepsilon \in P$, then S is not allowed in any right hand side
  - Consequence: Rules (almost) never derive shorter words

The Chomsky hierarchy (2)

$$G = \langle V_N, V_T, P, S \rangle \tag{19}$$

- G is of Type 2 or *context-free*
  if all productions are of the form

$$A \rightarrow \beta \text{ with } A \in V_N; \beta \in VV^* \tag{20}$$

Exception:

$$S \rightarrow \varepsilon \in P \text{ is allowed, if } \beta \in (V \backslash \{S\})(V \backslash \{S\})^* \tag{21}$$

The Chomsky hierarchy (2)

$$G = \langle V_N, V_T, P, S \rangle \tag{19}$$

- G is of Type 2 or *context-free*
  if all productions are of the form

$$A \to \beta \text{ with } A \in V_N ; \beta \in VV^* \tag{20}$$

Exception:

$$S \to \varepsilon \in P \text{ is allowed, if } \beta \in (V \setminus \{S\})(V \setminus \{S\})^* \tag{21}$$

- Only single non-terminals are replaced
- If $S \to \varepsilon \in P$, then S is not allowed in any right hand side

The Chomsky hierarchy (3)

$$G = \langle V_N, V_T, P, S \rangle \tag{22}$$

- G is of Type 3 or *right-linear* (*regular*) if all productions are of the form

$$A \to aB \text{ or} \tag{23}$$

$$A \to a \text{ with } A, B \in V_N; a \in V_T$$

Exception:

$$S \to \varepsilon \in P \;\text{ is allowed, if } B \in V_N \backslash \{S\} \tag{24}$$

The Chomsky hierarchy: exercises

$$G = \langle V_N, V_T, P, S \rangle \tag{25}$$

with

1. $V_N = \{S, A, B\}$,
2. $V_T = \{0\}$,
3. P :

$$\begin{array}{rcll} S & \rightarrow & \varepsilon & 1 \\ S & \rightarrow & ABA & 2 \\ AB & \rightarrow & 00 & 3 \\ 0A & \rightarrow & 000A & 4 \\ A & \rightarrow & 0 & 5 \end{array}$$

4. $S = S$.

The Chomsky hierarchy: exercises

$$G = \langle V_N, V_T, P, S \rangle \tag{25}$$

with

1. $V_N = \{S, A, B\}$,
2. $V_T = \{0\}$,
3. P :

$$\begin{array}{rcll} S & \rightarrow & \varepsilon & 1 \\ S & \rightarrow & ABA & 2 \\ AB & \rightarrow & 00 & 3 \\ 0A & \rightarrow & 000A & 4 \\ A & \rightarrow & 0 & 5 \end{array}$$

4. $S = S$.

a) What is G's highest type?
b) Show how G derives the word 00000.
c) Formally describe the language $L(G)$.
d) Define a regular grammar G' equivalent to G.

The Chomsky hierarchy: exercises (cont.)

An octal constant is a finite sequence of digits starting with `0` followed by at least one digit ranging from `0` to `7`. Define a regular grammar encoding exactly the set of possible octal constants.

Context-free grammars

- Reminder: $G = \langle V_N, V_T, P, S\rangle$ is context-free, if all $l \rightarrow r \in P$ are of the form $A \rightarrow \beta$ with
  - $A \in V_N$ and $\beta \in VV^*$
  - (special case: $S \rightarrow \epsilon \in P$, then S is not allowed in any β)
- Context-free languages/grammars are highly relevant
  - Core of most programming languages
  - Algebraic expressions
  - XML
  - Many aspects of human language

Grammars in Practice

- Most programming languages are described by context-free grammars (with extra "semantic" constraints)
- Grammars generate languages
- PDAs and e.g. CYK-Parsing recognize words
- For compiler we need to ...
  - identify correct programs
  - and understand their structure!

Lexing and Parsing

- Lexer: Breaks programs into tokens
  - Smallest parts with semantic meaning
  - Can be recognized by regular languages/patterns
  - Example: `1, 2, 5` are all Integers
  - Example: `i, handle, stream` are all Identifiers
  - Example: `>, >=, *` are all individual operators
- Parser: Recognizes program structure
  - Language described by a grammar that has token types as terminals, not individual characters
  - Parser builds *parse tree*

Introduction: nanoLang

Our first language: *nanoLang*

- Simple but Turing-complete language
- Block-structured
  - Functions with parameters
  - Blocks of statements with local variables
- Syntax C-like" but simplified
  - Basic flow control (`if`, `while`, `return`)
- Simple static type system
  - Integers (64 bit signed)
  - Strings (immutable)

nanoLang "Hello World"

```
# The first ever nanoLang program

Integer main()
{
    print "Hello␣World\n";
    return 0;
}
```

More Substantial *nanoLang* Example

```
Integer hello(Integer repeat, String message)
{
    Integer i;
    i = 0;
    while(i<repeat)
    {
        print message;
        i = i+1;
    }
    return 0;
}

Integer main()
{
    hello(10, "Hello\n");
    return 0;
}
```

nanoLang Lexical Structure

- Reserved words:
  - `if`, `while`, `return`, `print`, `Integer`, `String`
- Comments: # to the end of the line
- Variable length tokens:
  - Identifier (letter, followed by letters and digits)
  - Strings (enclosed in double quotes (`"This is a string"`)
  - Integer numbers (non-empty sequences of digits)
- Other tokens:
  - Brackets: `(`,`)`, `{`,`}`
  - Operators: `+`, `-`, `*`, `/`
  - Comparison operators: `>`, `>=`, `<`, `<=`, `!=`
  - Equal sign = (used for comparison and assignments!)
  - Separators: `,`, `;`

nanoLang Program Structure

- A *nanoLang* program consists of a number of definitions
  - Definitions can define global variables or functions
  - All symbols defined in the global scope are visible everywhere in the global scope
- Functions accept arguments and return values
  - Functions consit of a header and a statement blocks
  - Local variables can be defined in statement blocks
- Statements:
  - `if`: Bedingte Ausführung
  - `while`: Schleifen
  - `return`: Return value from function
  - `print`: Print value to Screen
  - Assignment: Set variables to values
  - Function calls (return value ignored)
- Expressions:
  - Integers: Variables, numbers, `+`,`-`,`*`,`/`
  - Booleans: Compare two values of equal type

Exercise: Fibonacci in *nanoLang*

- Write a recursive and an iterative implementation of Fibonacci numbers in *nanoLang*

nanoLang Grammar (Bison format) (0 -tokens)

```
%start prog

%token OPENPAR CLOSEPAR
%left  MULT DIV
%left  PLUS MINUS
%token EQ NEQ LT GT LEQ GEQ
%token OPENCURLY CLOSECURLY
%token SEMICOLON COMA

%token <ident>  IDENT
%token <string> STRINGLIT
%token <intval> INTLIT
%token INTEGER STRING
%token IF WHILE RETURN PRINT

%token ERROR
```

nanoLang Grammar (Bison format) (1)

```
prog: /* Nothing */
    | prog def
;

def: vardef
   | fundef
;

vardef: type IDENT SEMICOLON
;

fundef: type IDENT OPENPAR params CLOSEPAR body
;

type: STRING
    | INTEGER
;
```

nanoLang Grammar (Bison format) (2)

```
params: /* empty */
    | paramlist
;

paramlist: type IDENT
         | type IDENT COMA paramlist
;

body: OPENCURLY vardefs stmts CLOSECURLY
;

vardefs: /* empty */
       | vardefs vardef
;

stmts: /* empty */
     | stmts stmt
```

nanoLang Grammar (Bison format) (3)

```
stmt: while_stmt
    | if_stmt
    | ret_stmt
    | print_stmt
    | assign
    | funcall_stmt
;

while_stmt: WHILE OPENPAR boolexpr CLOSEPAR body
;

if_stmt: IF OPENPAR boolexpr CLOSEPAR body
;

ret_stmt: RETURN expr SEMICOLON
;
```

nanoLang Grammar (Bison format) (4)

```
print_stmt: PRINT expr SEMICOLON
;

assign: IDENT EQ expr SEMICOLON
;

funcall_stmt: funcall SEMICOLON
;

boolexpr: expr EQ expr
        | expr NEQ expr
        | expr LT expr
        | expr GT expr
        | expr LEQ expr
        | expr GEQ expr
;
```

nanoLang Grammar (Bison format) (5)

```
expr: funcall
    | INTLIT
    | IDENT
    | STRINGLIT
    | OPENPAR expr CLOSEPAR
    | expr PLUS expr
    | expr MINUS expr
    | expr MULT expr
    | expr DIV expr
    | MINUS expr
;
```

nanoLang Grammar (Bison format) (6)

```
funcall: IDENT OPENPAR args CLOSEPAR
;

args: /* empty */
    | arglist
;

arglist: expr
       |expr COMA arglist
;
```

Exercise

- Write a *flex*-based scanner for *nanoLang*
  - At minimum, it should output the program token by token
  - Bonus: Find a way to keep track of line numbers for tokens
  - Superbonus: Also keep track of columns
- Reminder: Compiling `flex` programs:

```
flex -t myflex.l > myflex.c
gcc -o myflex myflex.c
```

Example output for Hello World

```
Integer = 277
main = 274
( = 258
) = 259
{ = 270
print = 282
"Hello World\n" = 275
; = 272
return = 281
0 = 276
; = 272
} = 271
```

Review: Goals for Today

- Refresher
- Reminder: Grammars and Chomsky-Hierarchy
  - Grammars
  - Regular languages and expressions
  - Context-free grammars and languages
- Syntactic structure of programming languages
- *nanoLang*
- Programming exercise: Tokenizing *nanoLang*

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
    - Optional: how would you improve it?

Goals for Today

- Refresher
- Syntax analysis revisited
  - The truth about Context-Free Grammars
  - Derivations and Parse Trees
  - Abstract Syntax Trees
- Programming exercise: Parsing *nanoLang*

Refresher

- Refresher
- Reminder: Grammars and Chomsky-Hierarchy
  - Grammars
  - Regular languages and expressions
  - Context-free grammars and languages
- Syntactic structure of programming languages
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The Truth about Context-Free Grammars (1)

- Reminder: G is of Type 2 or *context-free*
  if all productions are of the form

$$A \to \beta \text{ with } A \in V_N; \beta \in VV^* \tag{26}$$

  Exception:

$$S \to \varepsilon \in P \text{ is allowed, if } \beta \in (V \backslash \{S\})(V \backslash \{S\})^* \tag{27}$$

  - Only single non-terminals are replaced
  - If $S \to \varepsilon \in P$, then S is not allowed in any right hand side

The Truth about Context-Free Grammars (2)

- Question: Is *nanoLang* context-free?

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Yes/No, but ...

- Problem:

```
prog: /* Nothing */
    | prog def
;
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The Truth about Context-Free Grammars (2)

- Question: Is *nanoLang* context-free?
- Question: Is the *nanoLang* grammar context-free?

Yes/No, but ...

- Problem:

```
prog: /* Nothing */
    | prog def
;
```

- `prog` is the start symbol
  - `prog` $\rightarrow \epsilon$
  - `prog` $\rightarrow$ `prog def`

The Truth about Context-Free Grammars (3)

- Chomsky's original definition:
  G is of Type 2 or *context-free*
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$$A \rightarrow \beta \text{ with } A \in V_N; \beta \in V^* \tag{28}$$

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$$A \to \beta \text{ with } A \in V_N; \beta \in V^* \quad (28)$$

Fact: Every Chomsky-CF-Grammar can be converted into a FLA-CF-Grammar!

Exercise: Eliminating ϵ rules

- Consider the following productions:
  1. $S \rightarrow \epsilon$
  2. $S \rightarrow A; S$
  3. $A \rightarrow i = n$
- Upper-case letters are non-terminals, S is the start symbol
  - Specify V_N and V_T
  - Create an equivalent FLA-CF-Grammar
  - Can you give a general method to convert Chomsky-CF-grammars to FLA-CF-gammars?

A Running Example

- We will consider the set of well-formed expressions over $x, +, *.(,)$ as an example, i.e. $L(G)$ for G as follows
  - $V_N = \{E\}$
  - $V_T = \{(,), +, *, x\}$
  - Start symbol is E
  - Productions:
    1. $E \rightarrow x$
    2. $E \rightarrow (E)$
    3. $E \rightarrow E + E$
    4. $E \rightarrow E * E$

Derivations

Definition: Assume a Grammar G. A derivation of a word w_n in $L(G)$ is a sequence $S \Longrightarrow w_1 \Longrightarrow \ldots \Longrightarrow w_n$ where S is the start symbol, and each w_i is generated from its predecessor by application of a production of the grammar

- Example: Consider our running example. We bold the replaced symbol. The following is a derivation of $x + x + x * x$:

$$
\begin{array}{ll}
 & \mathbf{E} \\
\Longrightarrow & \mathbf{E} + E \\
\Longrightarrow & E + E + \mathbf{E} \\
\Longrightarrow & \mathbf{E} + E + E * E \\
\Longrightarrow & x + \mathbf{E} + E * E \\
\Longrightarrow & x + x + \mathbf{E} * E \\
\Longrightarrow & x + x + x * \mathbf{E} \\
\Longrightarrow & x + x + x * x
\end{array}
$$

Rightmost/Leftmost Derivations

Definition:

- A derivation is called a rightmost derivation, if at any step it replaces the rightmost non-terminal in the current word.
- A derivation is called a leftmost derivation, if at any step it replaces the leftmost non-terminal in the current word.

- Examples:
  - The derivation on the previous slide is neither leftmost nor rightmost.
  - $\mathbf{E} \Longrightarrow E + \mathbf{E} \Longrightarrow E + E + \mathbf{E} \Longrightarrow E + E + E * \mathbf{E} \Longrightarrow E + E + \mathbf{E} * x \Longrightarrow E + \mathbf{E} + x * x \Longrightarrow \mathbf{E} + x + x * x \Longrightarrow x + x + x * x$ is a rightmost derivation.

Parse trees

Definition: A parse tree for a derivation in a grammar $G = \langle V_N, V_T, P, S\rangle$ is an ordered, labelled tree with the following properties:

- Each node is labelled with a symbol from $V_N \cup V_T$
- The root of the tree is labelled with the start symbol S.
- Each inner node is labelled with a single non-terminal symbol from V_N
- If an inner node with label A has children labelled with symbols $\alpha_1, \ldots, \alpha_n$, then there is a production $A \rightarrow \alpha_1 \ldots \alpha_n$ in P.

- The parse tree represents a derivation of the word formed by the labels of the leaf nodes
- It abstracts from the order in which productions are applied.

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Consider the following derivation:

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It can be represented by a sequence of parse trees:

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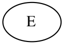

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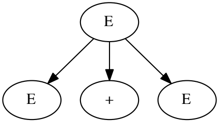

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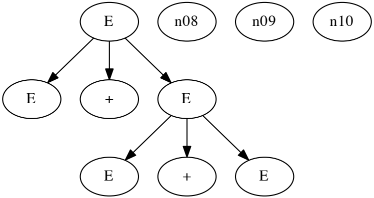

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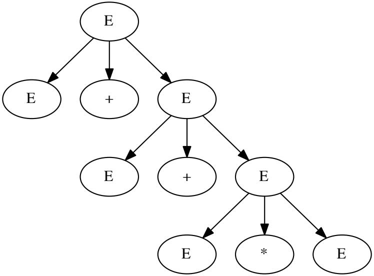

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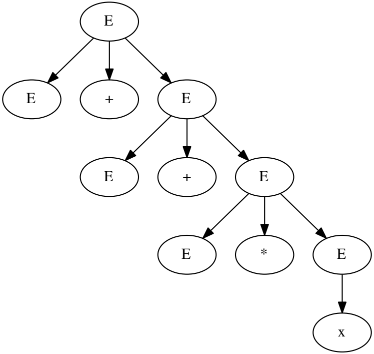

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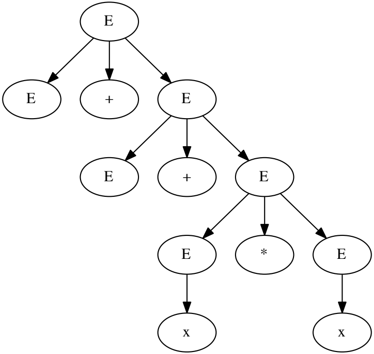

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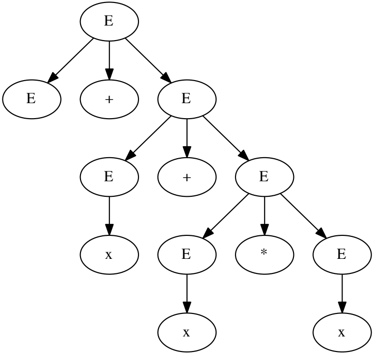

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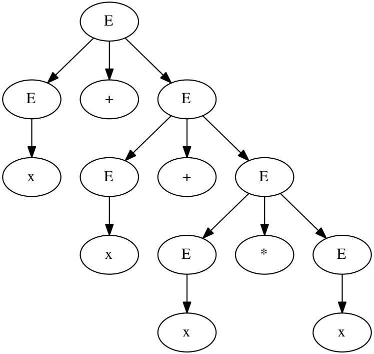

Ambiguity

Definition: A grammar $G = \langle V_N, V_T, P, S \rangle$ is ambiguous, if it has multiple different parse trees for a word w in $L(G)$.

- Consider our running example with the following productions:
  1. $E \rightarrow x$
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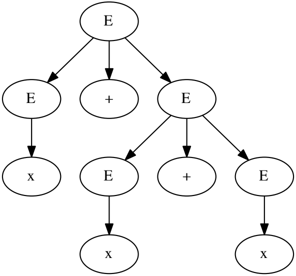
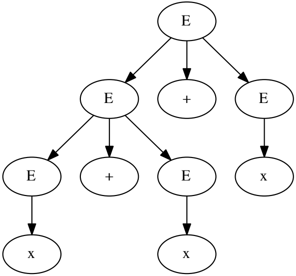
- The following 2 parse trees represent derivations of $x + x + x$:





Exercise: Ambiguity is worse. . .

- Consider our example and the parse trees from the previous slide:
  1. $E \to x$
  2. $E \to (E)$
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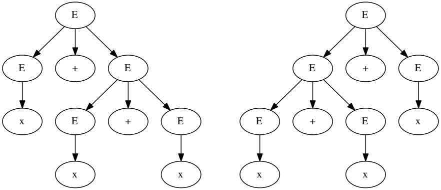

- Provide a rightmost derivation for the right tree.
- Provide a rightmost derivation for the left tree.
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- Provide a leftmost derivation for the right tree.

Exercise: Eliminating Ambiguity

- Consider our running example with the following productions:
  1. $E \rightarrow x$
  2. $E \rightarrow (E)$
  3. $E \rightarrow E + E$
  4. $E \rightarrow E * E$
- Define a grammar G' with $L(G) = L(G')$ that is not ambiguous, that respects that $*$ has a higher precedence than $+$, and that respects left-associativity for all operators.

Flex/Bison Interface

- Bison callse function `yylex` to get the next token
- `yylex` executes user rules (pattern/action)
  - User actions return token (integer value)
  - Additionally: `yylval` can be set and is available in Bison via the `$$/$1/ldots` mechanism
- `yylval` provides the *semantic value* of a token
  - For complex languages: Use a pointer to a struct
    - Content: Position, string values, numerical values, ...
  - Type of `yylval` if set in *Bison* file!

    `%define api.value.type {YourType}`

Grading Exercise 2

- Write a Bison parser for *nanoLang*
  - Bonus: Translate *nanoLang* into Abstract Syntax Trees (will be required next week!)

Review: Goals for Today

- Refresher
- Syntax analysis revisited
  - The truth about Context-Free Grammars
  - Derivations and Parse Trees
  - Abstract Syntax Trees

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Refresher
- Revisiting derivations, parse trees, abstract syntax trees
- Walk-through: Parsing expressions in practice
- Programming exercise: ASTs for *nanoLang*

Refresher

- Refresher
- Syntax analysis revisited
  - The truth about Context-Free Grammars
  - Derivations and Parse Trees
  - Abstract Syntax Trees
- Programming exercise: Parsing *nanoLang* (i.e. writing a program that accepts syntactically correct *nanoLang* programs and rejects syntactially incorrect ones (due next week)

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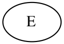

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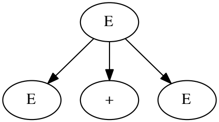

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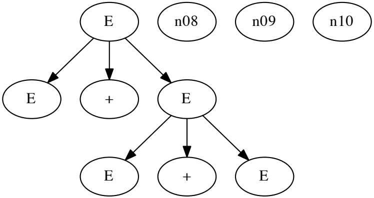

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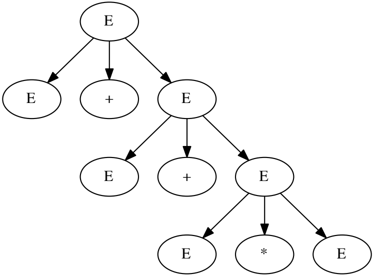

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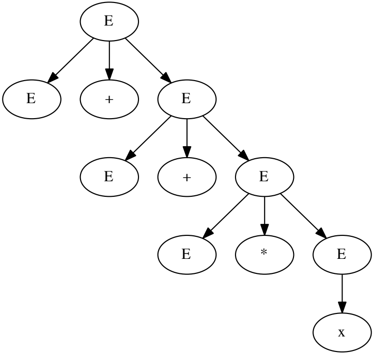

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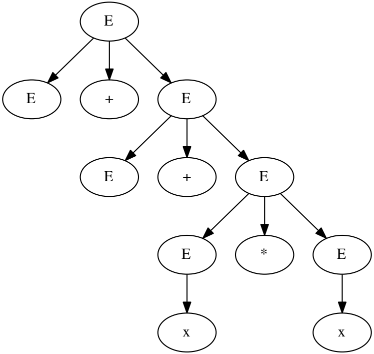

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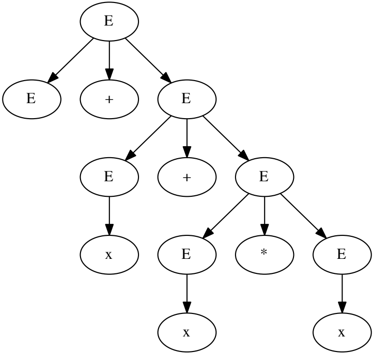

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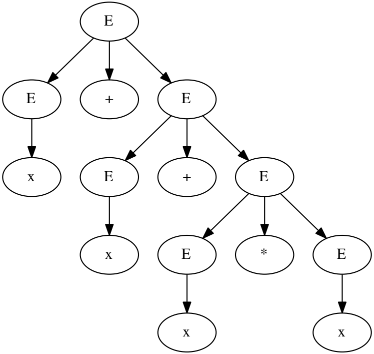

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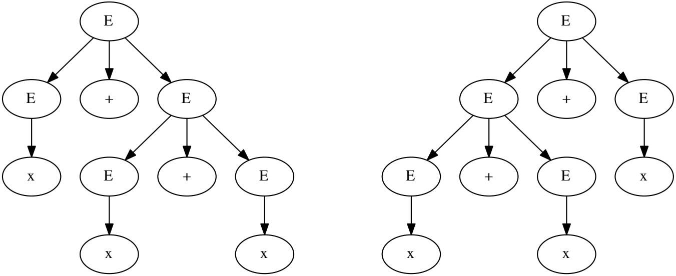

Exercise: Ambiguity is worse...

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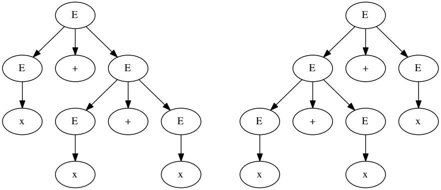

- Provide a rightmost derivation for the right tree.
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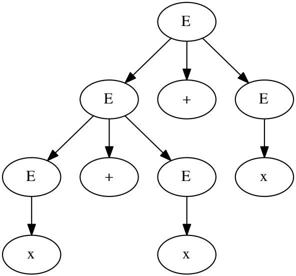
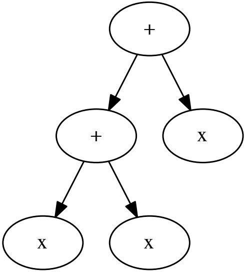
Abstract Syntax Trees

- Abstract Syntax Trees represent the structure of a derivation without the specific details
- Think: "Parse trees without the syntactic sugar"
- Example:

Parse Tree:



Corresponding AST:



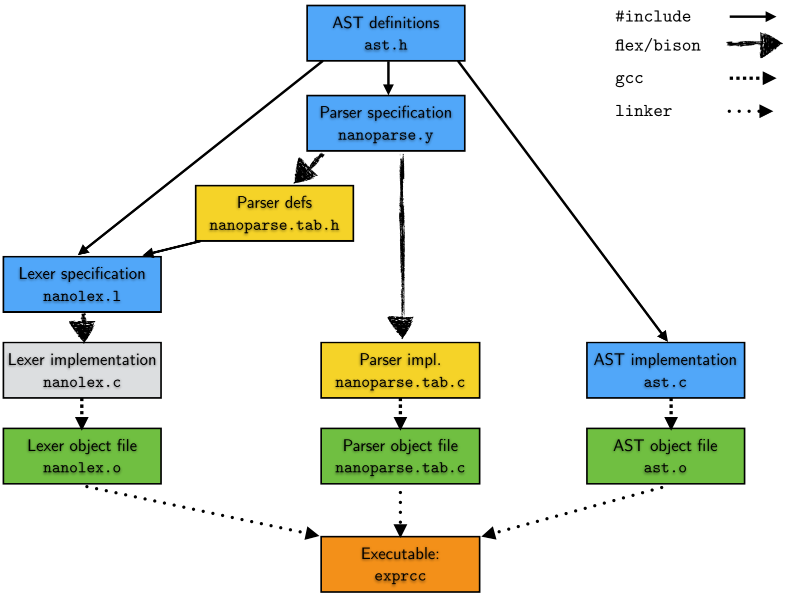
From text to AST in practice: Parsing *nanoLang* expressions

- Example for syntax analysis and building abstract syntax trees
- Language: *nanoLang* expressions (without function calls)
- Structure of the project
- Building
- Code walk-through

Exercise: Building `exprcc`

- Go to
  `http://wwwlehre.dhbw-stuttgart.de/~sschulz/cb2015.html`
- Download `NANOEXPR.tgz`
- Unpack, build and test the code
- To test:
  - `./exprcc expr1.nano`
  - `./exprcc --sexpr expr1.nano`
  - `./exprcc --dot expr1.nano`

exprcc Overview



exprcc Makefile

A first Abstract Syntax Tree

- Test expression: `-a+b*(c+d)`
- Corresponding AST?

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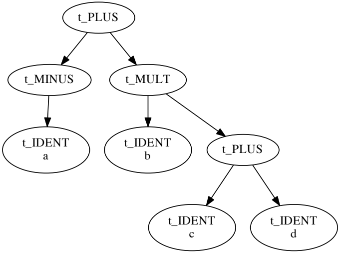


Simplified *nanoLang* expression syntax

```
expr: INTLIT
    | IDENT
    | STRINGLIT
    | OPENPAR expr CLOSEPAR
    | expr PLUS expr
    | expr MINUS expr
    | expr MULT expr
    | expr DIV expr
    | MINUS expr
;
```

Alternative notation

```
expr -> INTLIT
      | IDENT
      | STRINGLIT
      | ( expr )
      | expr + expr
      | expr - expr
      | expr * expr
      | expr / expr
      | - expr
```

Alternative notation

```
expr -> INTLIT
      | IDENT
      | STRINGLIT
      | ( expr )
      | expr + expr
      | expr - expr
      | expr * expr
      | expr / expr
      | - expr
```

Question: Is the grammar unambiguous?

Alternative notation

```
expr -> INTLIT
      | IDENT
      | STRINGLIT
      | ( expr )
      | expr + expr
      | expr - expr
      | expr * expr
      | expr / expr
      | - expr
```

Question: Is the grammar unambiguous?

- How do we solve this?

Precedences and Associativity in Bison

- Code: `nanoparse.y` token definitions
- The trick with unary `-`

Implementing ASTs

- Code: `ast.c`, `ast.h`

- Code: `nanolex.l`

Building ASTs

- Code: `nanoparse.y` syntax rules and semantic actions

Grading Exercise 3

- Extend the *nanoLang* parser to generate abstract syntax trees *nanoLang* programs
  - You can use your own parser or extend the expression parser from this lecture
  - Due date: Our lecture on April 22nd

Review: Goals for Today

- Refresher
- Revisiting derivations, parse trees, abstract syntax trees
- Walk-through: Parsing expressions in practice
- Programming exercise: ASTs for *nanoLang*

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
    - Optional: how would you improve it?

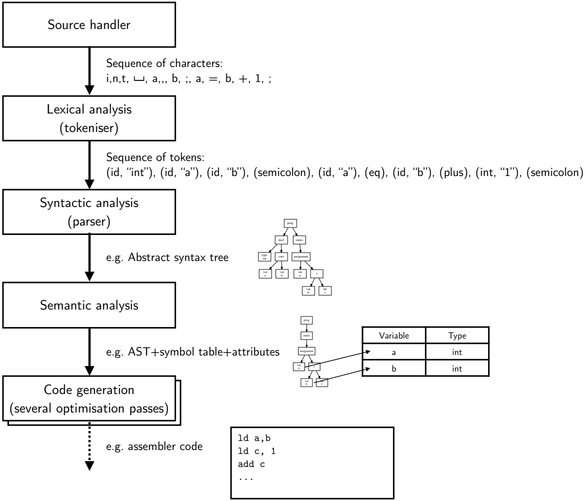
Goals for Today

- Refresher
- Semantic properties
  - Names, variables, identifiers
  - Visibility and scopes
  - Simple types and type systems
- Symbol tables
- Memory organisation and storage locations

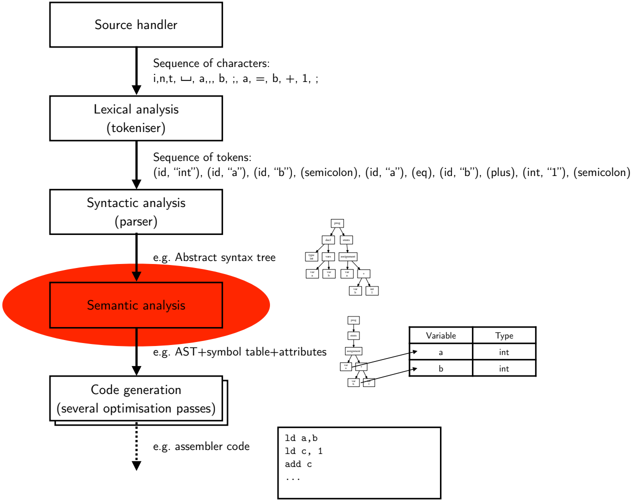
Refresher

- Formal definition of parse trees
- Ambiguity and derivation types
- Abstract syntax trees
- Syntax analysis in practice
  - *nanoLang* expression parser
  - Abstract syntax tree datatype and algorithms
  - Parsing *nanoLang* expressions with Bison
- Programming exercise: Parsing *nanoLang* into abstract syntax trees

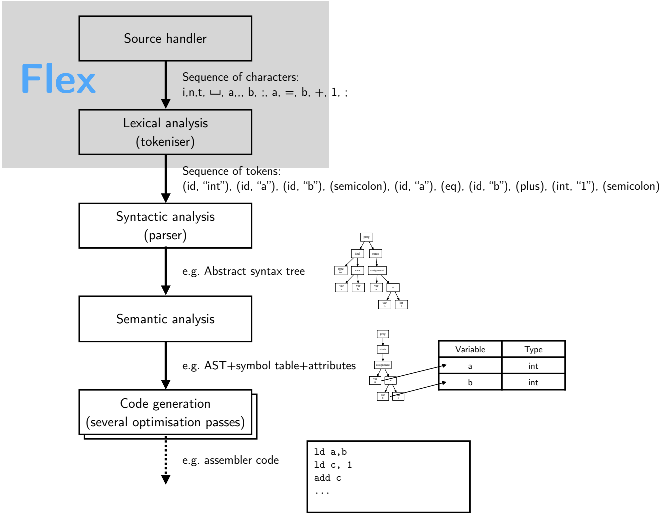
High-Level Architecture of a Compiler



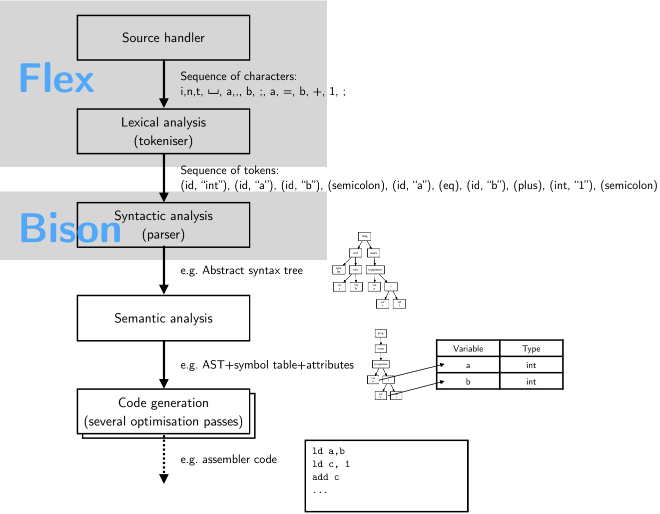
High-Level Architecture of a Compiler



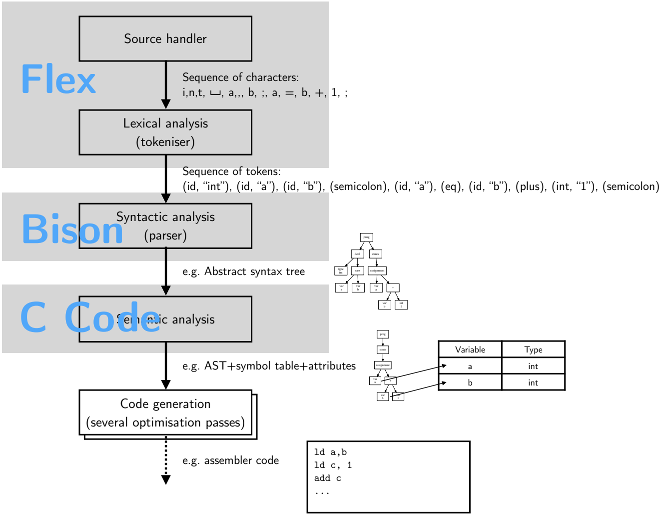
High-Level Architecture of a Compiler



High-Level Architecture of a Compiler



High-Level Architecture of a Compiler



Semantic Constraints

Group Exercise: Spot the Bugs (1)

```
Integer fun1(Integer i, Integer i)
{
    Integer i;

    if(i > 0)
    {
        print j;
    }
}

Integer main()
{
    fun1(1, 2);
    fun2(1, 2);
    return 0;
}
```

Group Exercise: Spot the Bugs (2)

```
Integer fun1(Integer i, Integer j)
{
    Integer i;

    if(i > "0")
    {
        print j+"12";
    }
    return 1;
}

Integer main()
{
    fun1(1, "Hello");
    fun2(1, 2, 3);
    return 0;
}
```

Group Exercise: Spot the Bugs (3)

```
Integer fun1(Integer i, Integer j)
{
    while(j>i)
    {
        Integer j;

        print j;
        j=j+1;
    }
    return 1;
}
```

Semantic constraints of *nanoLang* (V 1.0)

- Every name has to be defined before it can be used
- Every name can only be defined once in a given scope
- Functions must be called with arguments of the right type in the right order
- Operands of comparison operators must be of the same type
- Operands of the arithmetic operators must be of type `Integer`
- Every program must have a `main()`
- (Every function must have a `return` of proper type)

Managing Symbols

- Properties of identifiers are stored in a symbol table
  - Name
  - Type
- Properties of identifiers depend on part of the program under consideration!
  - Names are only visible in the scope they are declared in
  - Names can be redefined in new scopes

Managing Symbols

- Properties of identifiers are stored in a symbol table
  - Name
  - Type
- Properties of identifiers depend on part of the program under consideration!
  - Names are only visible in the scope they are declared in
  - Names can be redefined in new scopes

Symbol tables need to change when traversing the program/AST for checking properties and generating code!

Names and Variables

- Definition: A variable is a location in memory (or "in the store") that can store a value (of a given type)
  - Variables can be statically or dynamically allocated
    - Typically: global variables are statically allocated (and in the data segment of the process
    - Local variables are dynamically managed and on the stack
    - Large data structures and objects are stored in the heap
- Definition: A *name* is an identifier that identifies a variable (in a given scope)
  - The same name can refer to different variables (recursive function calls)
  - Different names can refer to the same variables (depends on programming languages - aliasing

Scopes and Environments

- The environment establishes a mapping from names to variables
- Static scope: Environment depends on block structure of the language
  - In any situation, the name refers to the variable defined in the neares surrounding block in the program text
  - Examples: C (mostly), Pascal, Java, modern LISPs (mostly)
- Dynamic scope: Environment depends on calling sequence in program
  - Name refers to the same variable it referred to in the calling function
  - Traditional LISP systems (Emacs LISP)

Group exercise: Static and dynamic scopes

```c
#include <stdio.h>
int a=10;
int b=10;
#define adder(x) (x)+a

void machwas(int a, int c)
{
    printf("adder(a)=%d\n", adder(a));
    printf("adder(b)=%d\n", adder(b));
    printf("adder(c)=%d\n", adder(c));
    {
        int c = 5;
        printf("adder(c)=%d\n", adder(c));
    }
}

int main(void)
{
    machwas(1, 2);
    machwas(2, 3);

    return 0;
}
```

Example: Scopes in *nanoLang*

```
Integer i;

Integer fun1(Integer loop)
{
    Integer i;

    i=0;
    while(i<loop)
    {
        i=i+1;
        print "Hallo";
    }
}

Integer main()
{
    i = 5;
    fun1(i);
}
```

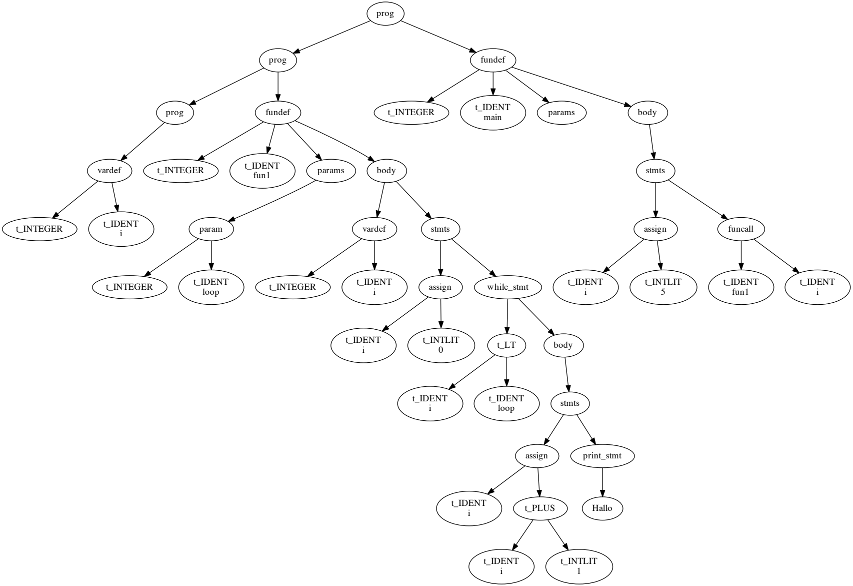
Scopes in *nanoLang*

- Global scope
  - Global variables
  - Functions
- Function scope
  - Function parameters
- Block scope
  - block-local variables

Example: Scopes in *nanoLang*

```
Integer i;

Integer fun1(Integer loop)
{
    Integer i;

    i=0;
    while(i<loop)
    {
        i=i+1;
        print "Hallo";
    }
}

Integer main()
{
    i = 5;
    fun1(i);
}
```

Walking the AST



Static type checking

- Types are associated with variables
- Types are checked at compile time or development time
- Advantages:
  - ?
- Disadvantages:
  - ?
- Typically used in:
  - ?

Dynamic type checking

- Types are associated with values
- Types are checked at run time
- Advantages:
  - ?
- Disadvantages:
  - ?
- Typically used in:
  - ?

No type checking

- Programmer is supposed to know what (s)he does
- Types are not checked at all
- Advantages:
  - ?
- Disadvantages:
  - ?
- Typically used in:
  - ?

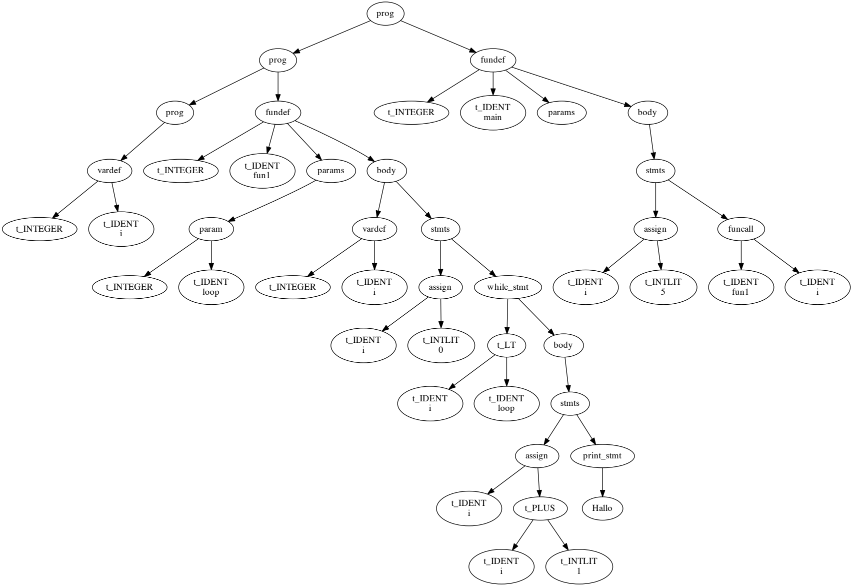
Exercise: How many types occur in this example?

```
Integer i;

Integer fun1(Integer loop)
{
    Integer i;

    i=0;
    while(i<loop)
    {
        i=i+1;
        print "Hallo";
    }
}

Integer main()
{
    i = 5;
    fun1(i);
}
```

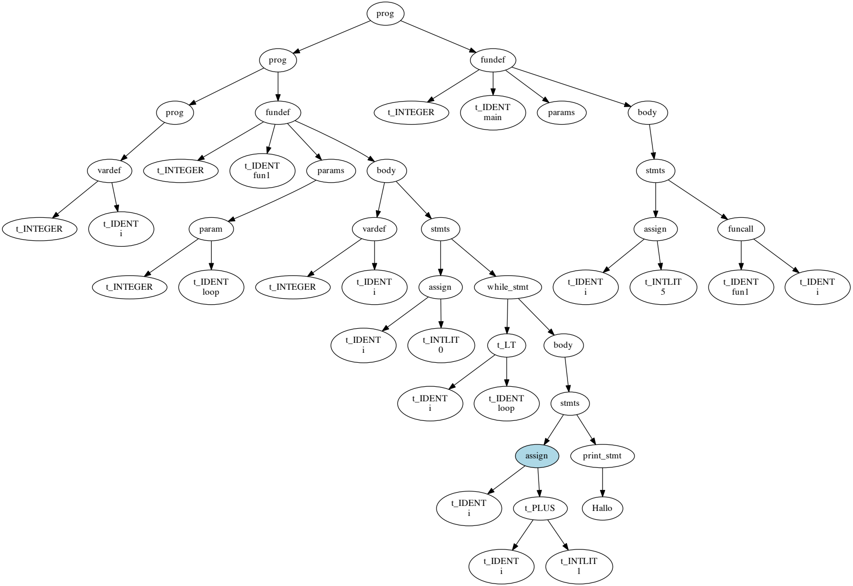
Symbol tables

- Store name (identifier) and type
- Nested for each scope:
  - Global scope
  - Each new scope entered will result in a new symbol table for that scope, pointing to the preceeding (larger scope)
- Local operations:
  - Add name/type (error if already defined)
- Global operations:
  - Find name (finds “nearest” matching entry, or error)
  - Enter new scope (creates a new empty symbol table pointing to the predecessor (if any)
  - Leave scope (remove current scope)

Walking the AST



Walking the AST



Representing types

- Types table:
  - Numerical encoding for each type
  - *Recipe* for each type
    - *nanoLang* basic types are atomic
    - Atomic types can also be addressed by name
    - Function types are vectors of existing types
- E.g.

Encoding	Type	Recipe
0	`String`	atomic
1	`Integer`	atomic
2	`Integer fun(Integer, String)`	(1, 1, 0)

- Operations:
  - Find-or-insert type
    - Return encoding for a new type
    - If type does not exist yet, create it

Programming Exercise

- Develop data structures for representing *nanoLang* types
- Develop data structures for implementing nested symbol tables

Review: Goals for Today

- Refresher
- Semantic properties
  - Names, variables, identifiers
  - Visibility and scopes
  - Simple types and type systems
- Symbol tables
- Memory organisation and storage locations

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Refresher
- Symbol Tables in practice
- Type inference and type checking
- Exercise: Build symbol tables

Refresher

- Semantic properties
  - Names, variables, identifiers
  - Visibility and scopes
  - Simple types and type systems
- Symbol tables
- Memory organisation and storage locations

The Big Picture: Type Checking

- We need to know the type of every expression and variable in the program
  - . . . to detect semantic inconsistencies
  - . . . to generate code
- Some types are simple in *nanoLang*
  - String constants are type `String`
  - Integer constants are type `Integer`
  - Results of arithmetic operations are `Integer`
- Harder: What to do with identifiers?
  - Type of the return value of a function?
  - Types of the arguments of a function?
  - Types of the values of a variable?

The Big Picture: Type Checking

- We need to know the type of every expression and variable in the program
  - ... to detect semantic inconsistencies
  - ... to generate code
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  - String constants are type `String`
  - Integer constants are type `Integer`
  - Results of arithmetic operations are `Integer`
- Harder: What to do with identifiers?
  - Type of the return value of a function?
  - Types of the arguments of a function?
  - Types of the values of a variable?

The answers depend on the definitions in the program!

Symbol Tables

- Symbol tables associate identifiers and types
- Symbol tables form a hierarchy
  - Symbols can be redefined in every new context
  - The "innermost" definition is valid
- Symbol tables are filled top-down
  - Outermost symbol-table contains global definitions
  - Each new context adds a new layer
  - Search for a name is from innermost to outermost symbol table

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer
i	Integer

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer
i	Integer

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer
i	Integer
-	-

Building Symbol Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer
i	Integer
-	-

i	Integer
fun1	(Integer)→Integer
main	()→Integer
-	-
-	-

Simplified Type Handling

- Handling complex types directly is cumbersome
- Better: Manage types separately
  - Types are stored in a separate table
  - Symbol table only needs to handle indices into type table

Symbol Tables and Type Tables

Program

```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

Symbol table

i	1
fun1	2
main	3
loop	1
i	1
-	-

i	1
fun1	2
main	3
-	-
-	-

Type table

1	Integer
2	(Integer)→Integer
3	()→Integer

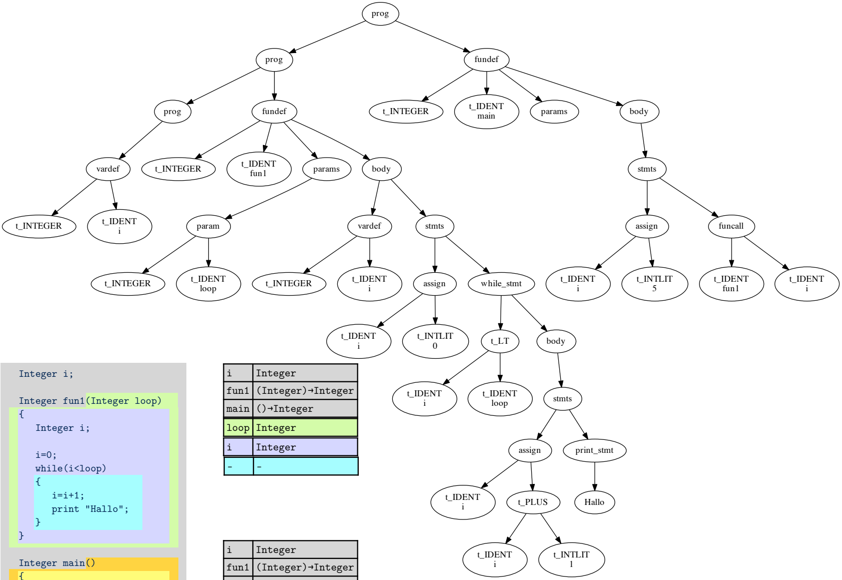
Type Inference in *nanoLang*

- Goal: Determine the (result) type of every expression in the program
- Process: Process AST `bottom-up`
  - Constants: “natural” type
  - Variables: Look up in symbol table
  - Function calls: Look up in symbol table
    - If arguments are not of proper type, error
    - Otherwise: return type of the function
  - Arithmetic expressions:
    - If arguments are `Integer`, result type is `Integer`
    - Otherwise: error

Contrast: Aspects of Type Inference in C

- Arithmetic expressions:
  - Roughly: arithmetic types are ordered by size (`char` < `int` < `long` < `long long` < `float` < `double`)
  - Type of `a + b` is the greater of the types of `a` and `b`
- Arrays
  - If `a` is an array of `int`, than `a[1]` is of type `int`
- Pointers
  - If `a` is of type `char*`, then `*a` is of type `char`
- Many more cases:
  - Structures
  - Enumerations
  - Function pointers

Symbol Tables and the AST




```
Integer i;

Integer fun1(Integer loop)
{
   Integer i;

   i=0;
   while(i<loop)
   {
      i=i+1;
      print "Hallo";
   }
}

Integer main()
{
   i = 5;
   fun1(i);
}
```

i	Integer
fun1	(Integer)→Integer
main	()→Integer
loop	Integer
i	Integer
-	-

i	Integer
fun1	(Integer)→Integer
main	()→Integer
-	-
-	-

Implementation Examples

- `main()` in `nanoparse.y`
- `STBuildAllTables()` in `semantic.c`
- `symbols.h` and `symbols.c`
- `types.h` and `types.c`

Grading Exercise 4

Extend your compiler project by computing the relevant symbol tables for all nodes of your AST

- Develop a type table date type for managing different types
- Define a symbol table data type for managing symbols and their types
  - Use a hierarchical structure
  - Suggested operations:
    - `EnterScope()`
    - `LeaveScope()`
    - `InserSymbol()` (with type)
    - `FindSymbol()` (return entry including type)
    - ...
- Traverse the AST in a top-down fashion, computing the valid symbol table at each node
- Annotate each AST node with the symbol table valid at that node

At the end, print all symbols and types of the global, top-level symbol table!

Example Output

```
> ncc NANOEXAMPLES/scopes.nano
Global symbols:
---------------
i                    : Integer
fun1                 : (Integer) -> Integer
main                 : () -> Integer

Types:
------
0: NoType
1: String
2: Integer
3: (Integer) -> Integer
4: () -> Integer
```

Review: Goals for Today

- Symbol Tables in practice
- Type inference and type checking
- Exercise: Build symbol tables

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Refresher
- Excursion: `assert()` in C
- Code generation considerations
  - Parameter passing
  - Assignments
  - Calling conventions
  - Runtime support
  - Libraries
- *nanoLang* runtime
  - Parameter passing
  - *nanoLang* string semantics
  - *nanoLang* library functions and OS interaction
- Exercise: Type checking

Refresher

- Symbol Tables in practice (top-down traversal)
- Type inference and type checking (bottom-up traversal)
- Example code walk-through
- Exercise: Build symbol tables

Excursion: `assert()`

- `assert()` is a facility to help debug programs
  - Part of the C Standard since C89
  - To use, `#include <assert.h>`
- `assert(expr)` evaluates `expr`
  - If `expr` is false, then an error message is written and the program is aborted
  - Otherwise, nothing is done
- Hints:
  - Particularly useful to check function parameter values
  - To disable at compile time, define the macro `NDEBUG` (e.g. with the compiler option `-DNDEBUG`
  - Useful idiom: `assert(expr && "What's wrong");`
  - More information: `man assert`

Semantics of Compiled and Target Language

- Before we can compile a language, we must understand its semantics
- Important questions:
  - How are parameter passed into functions?
  - Related: How do assignments work?
- Before we can compile a language, we must understand the target language and environment
  - How are parameters and local variables handled?
  - How does the program interact with the OS and the environment?

Parameter Passing

- Call by value
  - Formal parameters become new local variables
  - Actual parameters are evaluated and used to initialize those variables
  - Changes to variables are irrelevant after function terminates
- Call by reference
  - Only *references* to existing variables are passed
  - In effect, formal parameters are bound to *existing* variables
  - Actual parameters that are not variables themselves are evaluated and placed in anonymous new variables
  - Changes to paramters in functions change the original variable
- ~~Call by name~~
  - Only historically interesting
  - Semantics mostly similar to *call-by-value*

Parameter Passing - Advantages and Disadvantages?

- Call by value?
- Call by reference?

Parameter Passing - Advantages and Disadvantages?

- Call by value?
- Call by reference?
- For your consideration:

```
int fun(int a, int b)
{
    a++;
    b++;
    return a+b;
}

int main(void)
{
    int i=0;

    fun(i,i);
    printf("i=%d\n", i);
}
```

Parameter Passing in C/C++/Pascal/Scheme?

- C?
- C++?
- Pascal?
- LISP/Scheme?
- Others?

Assignments

- What happens if `a = b;` is encountered?
  - If both are integer variables?
  - If both are string variables?
  - If both have an object type?
  - If both are arrays?

Calling conventions

- How are paramters values passed at a low level?
  - Registers?
  - Stack?
  - Other?
- Who is responsible for preserving registers?
  - Caller?
  - Callee?
- In which order are parameters passed?
- How is the old context (stack frame and PC) preserved and restored?

Calling conventions

- How are paramters values passed at a low level?
  - Registers?
  - Stack?
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- Who is responsible for preserving registers?
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- In which order are parameters passed?
- How is the old context (stack frame and PC) preserved and restored?

For our *nanoLang* compiler, we rely on C to handle these things!

Runtime system and OS Integration

- Runtime system provides the glue between OS and program
  - Translates OS semantics/conventions to compiled language and back
- Runtime system provides execution support for program semantics
  - Higher-level functions/data types
  - Memory management
  - Library functions

Parameter passing and assignments in *nanoLang*

- Suggestion: All parameter passed "as if" by value
- Integer: Pass by value
- *Immutable strings*
  - Can be passed by reference
  - Need to be memory-managed (reference counting, a job for the runtime system)
  - Alternative is not simpler!

nanoLang OS integration

- Command line arguments
  - Suggestion: `main()` takes arbitrary number of string arguments
  - These are filled from the command line
  - Spare arguments are represented by the empty string
- Exit and return value
  - Library function `Exit(val)` terminates program and returns integer value
  - `return` from `main()` has the same effect

nanoLang Library Functions

- Suggested function to make things interesting:
  - `StrIsInt(str)`: Returns 1 if `str` encodes a valid integer, 0 otherwise
  - `StrToInt()`: Converts a string to an integer. If `str` is not an integer encoding, result is undefined
  - `IntToStr(int)`: Returns a string encoding of the given integer
  - `StrLength(str)`: Returns the lengths of str
- More sugegstions?
  - `String StrFront(str, int)` - return first `int` characters as new string
  - `String StrRest(str, int)` - return all but first `int` characters
  - `String StrCat(str, str)` - concatenate strings, return as new string
  - `Integer StrToASCII(str)` - only for strings of lenght 1, return ASCII value
  - `String ASCIIToStr(int)` - reverse of the above

nanoLang Strings

- Temptation: Use C `char*`
- Fails as soon as strings can be dynamically created
- Suggestion: Structure with reference counting
  - String value - the actual string (`malloc()`ed `char*`)
  - Length (maybe)
  - Reference count - how many places have a reference to the string?
    - Increase if string is assigned to a variable or passed to a function
    - Decrease, if a variable is reassigned or goes out of scope
    - Free string, if this reaches 0

Grading Exercise 5

Extend your compiler project by computing the types of all expressions in your system and check type constraints

- Check that variables are only assigned values of the right type
- Check that functions are only called with correctly typed parameters
- Check that operators have compatible types
- Check that comparisons only happen between expressions of the same type
- Bonus: Check that functions (always) return the correct type

Review: Goals for Today

- Excursion: `assert()` in C
- Code generation considerations
  - Parameter passing
  - Assignments
  - Calling conventions
  - Runtime support
  - Libraries
- *nanoLang* runtime
  - Parameter passing
  - *nanoLang* string semantics
  - *nanoLang* library functions and OS interaction

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Refresher
- Coding Hints
- Code generation *nanoLang* to C
- (Simple) Optimizations
- Exercise: Code generation (I)

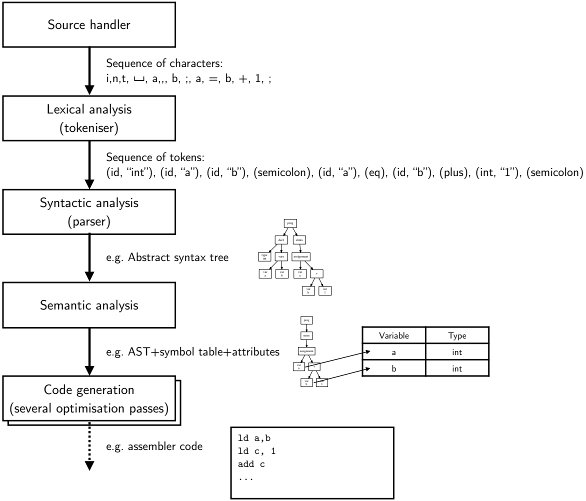
Refresher

- `assert()`
- General considerations for code generation
  - Semantics of parameters/assignments
  - Function calls
  - Runtime support and libraries
- Special considerations for *nanoLang*
  - Strings
  - Command line processing
  - Built-in library functions

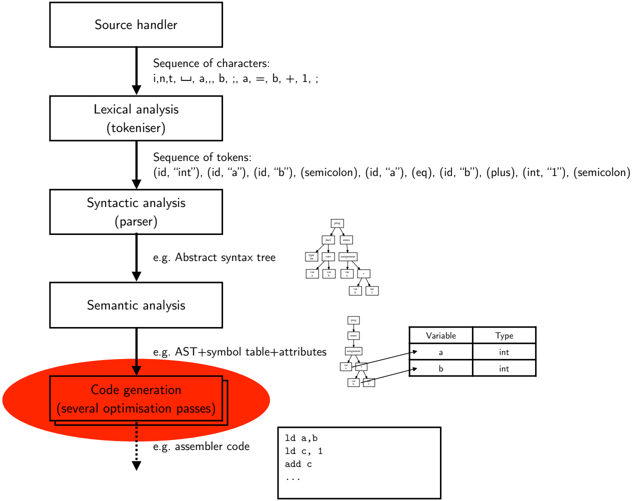
Coding hints

- The *nanoLang* compiler is a non-trivial piece of software
  - Several modules
  - Several different data types (AST, Types, Symbols)
- It helps to follow good coding practices
  - The big stuff: Good code structure
    - One function per function
    - Not more than one screen page per function
  - The small stuff
    - Clean formatting (including vertical space)
    - Use expressive names for functions and variables
    - Reasonable comments (don't over-comment, though!)
    - Use `assert()`
    - Compile with warnings enables (Makefile: `CFLAGS = -Wall`)

The Final Phase



The Final Phase



Code Generation `nanoLang` to C

- Suggestion: Code generation uses separate phases
  - Initial boilerplate
  - Global variable definitions
  - Function declarations
  - Constant library code
  - Translation of function definitions
  - C `main()` function

Name Mangling

- To avoid name conflicts, nanoLang identifer should use a standard naming scheme
- Suggestion:
  - Atomic type names are prepended with `N_`
  - Function and variable names are prepended with `n_`

Initial boilerplate

- Emit constant code needed for each translated *nanoLang* program
  - Comment header
  - Standard system includes
  - Type definitions
  - Possibly macro definitions
- Implementation via printing constant string
  - Easiest way
  - Alternative: Read from file

Global variable definitions

- Visibility difference between *nanoLang* and C
  - Globally defined *nanoLang* identifiers are visible throughout the program
  - C definitions are visible from the point of definition only
  - Hence we need to declare variables (and functions) upfront
- Implementation suggestion:
  - Iterate over all symbols in the global symbol table
  - For each variable symbol, emit a declaration

Function declarations

- The same visibility difference between *nanoLang* and C affects functions
  - We need to declare all functions upfront!
- Implementation suggestion:
  - Iterate over all symbols in the global symbol table
  - For each function symbol, emit a declaration

Function declarations

- The same visibility difference between *nanoLang* and C affects functions
  - We need to declare all functions upfront!
- Implementation suggestion:
  - Iterate over all symbols in the global symbol table
  - For each function symbol, emit a declaration

Suggestion: For simplicity and consistency, we should insert the *nanoLang* standard library functions (`Exit()`, `StrIsInt()`, `StrToInt`, ...) into the symbol table (and do so before semantic analysis to stop the user from inadvertently redefining them!)

Constant library code

- The *nanoLang* runtime will need various pieces of code
  - Data types and helper functions to handle e.g. Strings
  - Implementations of the build-in functions
- Implementation options
  - Just insert plain C code here (Alternative 0, but this may be lengthy)
  - Alternative 1: Read this C code from a file
  - Alternative 2: Just `#include` the full C code
  - Alternative 3: `#include` only header with declarations, then require linking with a run time library later

Translation of function definitions

- This is the heart of the compiler!
- Go over the AST and emit a definition for each function
  - *nanoLang* functions become C functions
  - Local *nanoLang* variables become C variables of an appropriate type
  - *nanoLang* blocks become C blocks
  - *nanoLang* instructions are translated into equivalent C statement sequences
  - Mostly straightforward
    - `print` requires case distinction
    - String comparisions require library calls

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More complex: Proper string handling

C `main()` function

- Generate an appropriate `main()` function
- Tasks:
  - Read commandline and initialize parameters for *nanoLang* `main()`
  - Call `nanoLang` main
  - Exit program, returning value from *nanoLang* `main`() to OS

Ideas for optimization

- Constant subexpression evaluation
- Common subexpression elimination
  - To do this well, we need to identify *pure* functions!
- Shift unneeded computations out of loop
- Eliminate computations of unused values

```
while(i<10)
{
      a = 3*10*i;
      b = 3*10*fun(a);
      i=i+1;
}
return a;
```

Grading Exercise 6

Extend your compiler project to generate a basic C programm

- Compile *nanoLang* statements into equivalent C statements
- Compile `nanoLang` definitions into C declarations and definitions
- Generate a basic `main()`
- For now, you can treat `String` as an imutable `char*` - we'll do the library next week

Review: Goals for Today

- Refresher
- Coding Hints
- Code generation *nanoLang* to C
- Optimizations
- Exercise: Code generation (I)

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Refresher
- Practical aspects of *nanoLang* code generation
- An introduction to top-down recursive descent parsing

Refresher

- Coding Hints
- Code generation *nanoLang* to C
  - Name handling
  - Global definitions
  - Libraries
  - Functions
  - ...
- Optimizations
  - Constant subexpressions
  - Common subexpressions (purely functional functions!)
  - Lift invariant expression out of loops
  - Eliminate computation of unused results
  - ...

Practical code generation for nanoLang

nanoLang C premable (1)

```
/*
 * Automatically generated by the nanoLang compiler ncc.
 *
 * The bolierplate and library code is released under the GNU General Public
 * Licence, version 2 or, at your choice, any later version.  Other code is
 * governed by the license of the original source code.
 */

#include <stdio.h>
#include <stdlib.h>
#include <string.h>

typedef long long N_Integer;
typedef char    *N_String;

#define NANO_MAKESTR(s) s
#define NANO_STRASSIGN(l, r) (l) = (r)
#define NANO_STRVAL(s) s

/* Global user variables */
```

nanoLang C premable (2)

```
/* Function declarations */

N_Integer        n_Exit(N_Integer);
N_Integer        n_StrIsInt(N_String);
N_Integer        n_StrToInt(N_String);
N_Integer        n_StrLen(N_String);
N_String         n_IntToStr(N_Integer);
N_String         n_StrFront(N_String, N_Integer);
N_String         n_StrRest(N_String, N_Integer);
N_String         n_StrCat(N_String, N_String);
N_Integer        n_StrToASCII(N_String);
N_String         n_ASCIIToStr(N_Integer);
N_String         n_testfun(N_Integer, N_String);
N_Integer        n_main(N_String, N_String);

/* nanoLang runtime library code */

/* String functions */

N_String         n_StrCat(N_String arg1, N_String arg2)
{
   size_t          len = strlen(arg1) + strlen(arg2) + 1;
   char           *res = malloc(len);
   strcpy(res, arg1);
   strcat(res, arg2);
   return res;
}
[...]
```

nanoLang and its translation (2)

```
String testfun(Integer count,
               String message)
{
   Integer i;
   String res;

   i=0;
   res="";

   while(i<count)
   {
      print "Schleifendurchlauf ";
      print i;
      print "\n";
      res = StrCat(res, message);
      i=i+1;
   }
   return res;
}
```

```
N_String n_testfun(N_Integer n_count,
                   N_String n_message)
{
   N_Integer       n_i = 0;
   N_String        n_res = 0;
   n_i = (0);
   NANO_STRASSIGN(n_res, (NANO_MAKESTR("")));
   n_res = (NANO_MAKESTR(""));
   while ((n_i) < (n_count)) {
      printf("%s", NANO_STRVAL((
            NANO_MAKESTR("Schleifendurchlauf "))));
      printf("%lld", (n_i));
      printf("%s", NANO_STRVAL((NANO_MAKESTR("\n"))));
      NANO_STRASSIGN(n_res, (n_StrCat((n_res),
                                       (n_message))));
      n_res = (n_StrCat((n_res), (n_message)));
      n_i = ((n_i) + (1));
   }
   return (n_res);
}
```

nanoLang and its translation (2)

```
Integer main(String arg1,
             String arg2)
{
   Integer limit;
   limit = 10;

   if(StrIsInt(arg1)=1)
   {
      limit=StrToInt(arg1);
   }

   print testfun(limit, arg2);
   print "\n";

   return 0;
}
```

```
N_Integer n_main(N_String n_arg1,
                 N_String n_arg2)
{
   N_Integer      n_limit = 0;
   n_limit = (10);
   if ((n_StrIsInt((n_arg1))) == (1)) {
      n_limit = (n_StrToInt((n_arg1)));
   }
   printf("%s", NANO_STRVAL((n_testfun((n_limit),
                             (n_arg2))))));
   printf("%s", NANO_STRVAL((NANO_MAKESTR("\n"))));
   return (0);
}
```

nanoLang C main

```
/* C main function */
int main (int argc, char *argv[])
{
    N_String arg1 = NANO_MAKESTR("");
    if (1 < argc) {
        arg1 = NANO_MAKESTR(argv[1]);
    }
    N_String arg2 = NANO_MAKESTR("");
    if (2 < argc) {
        arg2 = NANO_MAKESTR(argv[2]);
    }
    n_main(arg1, arg2);
}
```

Top-Down Parsing

Basic Idea of *Recursive Descent*

- One parsing function per non-terminal
- Initial function corresponds to start symbol
- Each function:
  - Uses an oracle to pick the correct production
  - Processes the right hand side against the input as follows:
    - If the next symbol is a terminal, it consumes that terminal from the input (if it's not in the input: error)
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Oracle: Based on next character to be read!

- Good case: Every production can be clearly identified
- Bad case: Common initial parts of right hand sides $\Longrightarrow$ **?**

Example/Exercise

- Consider the following productions from G_1:
  - $S \to aA$
  - $A \to Bb$
  - $B \to aA$
  - $B \to \epsilon$
- What is the language produced?
- How can we parse *aabb*?

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Left factoring!

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Left factoring! Plus. . .

Left recursion

Definition: A grammar $G = \langle V_N, V_T, P, S \rangle$ is left-recursive, if there exist $A \in V_N, w \in (V_N \cup V_T)^*$ with $A \stackrel{+}{\Longrightarrow} Aw$.

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- Left recursion leads to infinite loops in recursive descent parsers
  - To parse A, we first need to parse A ...
- Solution: Reformulate grammar

Our Running Example

- We will again consider the set of well-formed expressions over $x, +, *.(,)$ as an example, i.e. $L(G)$ for G as follows
  - $V_N = \{E\}$
  - $V_T = \{(,), +, *, x\}$
  - Start symbol is E
  - Productions:
    1. $E \rightarrow x$
    2. $E \rightarrow (E)$
    3. $E \rightarrow E + E$
    4. $E \rightarrow E * E$

Our Running Example (unambiguous)

- We will again consider the set of well-formed expressions over $x, +, *.(,)$ as an example, i.e. $L(G)$ for G as follows
  - $V_N = \{E, T, F\}$
  - $V_T = \{(,), +, *, x\}$
  - Start symbol is E
  - Productions:
    1. $E \to E + T$
    2. $E \to T$
    3. $T \to T * F$
    4. $T \to F$
    5. $F \to (E)$
    6. $F \to x$

Our Running Example (unambiguous)

- We will again consider the set of well-formed expressions over $x, +, *.(,)$ as an example, i.e. $L(G)$ for G as follows
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  - Productions:
    1. $E \rightarrow E + T$
    2. $E \rightarrow T$
    3. $T \rightarrow T * F$
    4. $T \rightarrow F$
    5. $F \rightarrow (E)$
    6. $F \rightarrow x$

What happens if we want to parse this using recursive descent?

Exercise: Recursive Descent for Expressions

- Consider the following productions:
  1. $E \rightarrow E + T$
  2. $E \rightarrow T$
  3. $T \rightarrow T * F$
  4. $T \rightarrow F$
  5. $F \rightarrow (E)$
  6. $F \rightarrow x$
- Can we find an equivalent grammar that can be top-down parsed?
- How?

Grading Exercise 7

Extend your compiler project to generate a basic C programm

- Finish the basic *nanoLang* compiler
  - Your program should produce a correct C program that compiles and implements the nanoLang semantics
  - A testprogram ("testprog3.nano") is on the web site.
- Bonus: Implement full string functionality (including automatic memory management and garbage collection)

Feedback round

- What was the best part of todays lecture?
- What part of todays lecture has the most potential for improvement?
  - Optional: how would you improve it?

Goals for Today

- Training exam
- Solution discussion

Review: Goals for Today

- Training exam
- Solution discussion

Feedback round

- What was the best part of the course?
- Suggestions for improvements?