Compiler Construction

Lecture 1: Introduction & Lexing

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January 30th, 2025

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Part I

Introduction

What is a compiler?

Compiler

What is a compiler?

Compiler

What is a compiler?

- A program that translates written text into text written in another language.
- Why translate source code?
  - Higher level.
  - Lower level.

Compiler

What is a compiler?

- A program that translates written text into text written in another language.
- Why translate source code?
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  - Lower level.

What is an interpreter

- A program that translates written text into an intermediate representation and immediately executes this.

Intrinsic merit

Compiler construction is challenging and fun

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- Many complex compilation steps
- Interesting conversion and analysis problems
- New architectures, new languages, new challenges

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Compiler construction poses some of the most interesting problems in computing.

Qualities of a compiler

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1. Correct code
2. Fast code
3. Fast compiler

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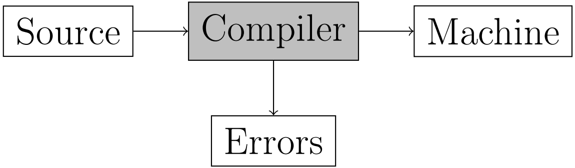
Qualities of a compiler

1. Correct code
2. Fast code
3. Fast compiler
4. Proportional compile time
5. Good diagnostics
6. Debugging support
7. Precise but flexible type system
8. Foreign function interface
9. Consistent and predictable optimisations
10. Energy saving executables
11. ...

Abstract view of a compiler

Compiler

Abstract view of a compiler



Abstract view of a compiler

Traditional two pass compiler

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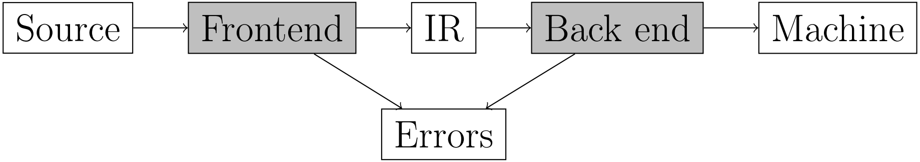

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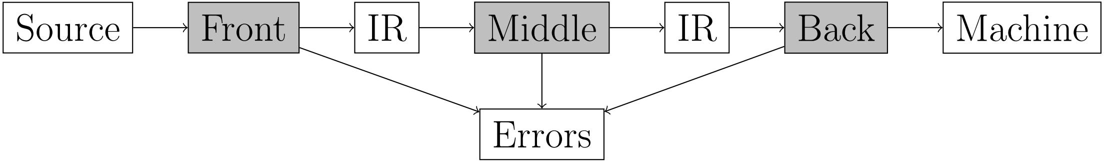

Frontend

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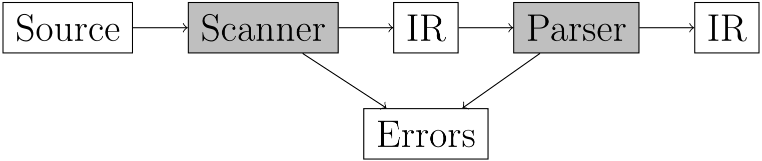

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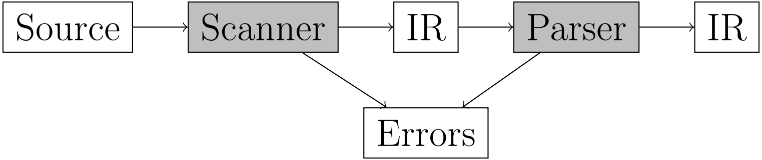

Duty of the frontend

- Recognise the (context-free) syntax
- Produce IR
- Report errors

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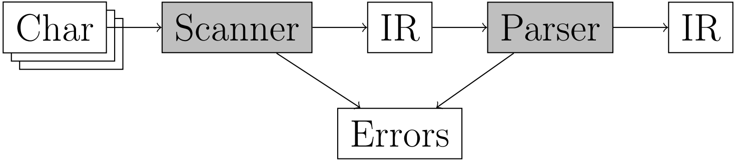

Duty of the scanner

- Translate source code:
  `x = val + 42;`

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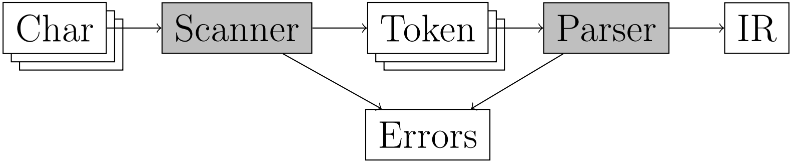

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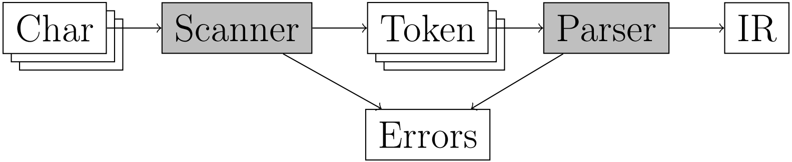

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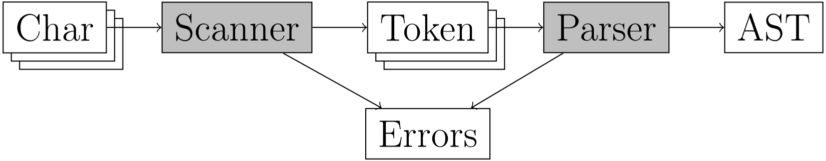
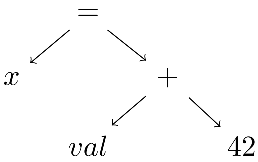


Duty of the parser

- Translate tokens:

  `<id,x> <sym,=> <id,val> <sym,+> <int,42> <sym,;>`
- To an abstract syntax tree:



Parser

Context-free syntax

Grammar

$$
\begin{array}{rcl}
\mathit{list} & ::= & \mathit{nil} \\
 & | & \mathit{cons}\ \ \mathit{elem}\ \ \mathit{list}
\end{array}
$$

Parser

Context-free syntax

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Backus-Naur form (BNF)

A grammar is:

$$G = (S, N, T, P)$$

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Backus-Naur form (BNF)

A grammar is:

$$G = (S, N, T, P)$$

where

S	is the start symbol
N	is the set of non-terminal symbols
T	is the set of terminal symbols
P	is the set of productions: $P : N \to (N \cup T)^+$

Expression grammar

$$
\begin{array}{rrcl}
1 & goal & ::= & expr \\
2 & expr & ::= & expr\ op\ term \\
3 & & | & term \\
4 & term & ::= & number \\
5 & & | & id \\
6 & op & ::= & + \\
7 & & | & -
\end{array}
$$

Parser

Example grammar

Expression grammar

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\begin{array}{llcl}
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\end{array}
$$

BNF

$$
\begin{array}{ll}
S & = goal \\
T & = number\ , id\ , +\ , - \\
N & = goal\ , expr\ , term\ , op \\
P & = 1, 2, 3, 4, 5, 6, 7
\end{array}
$$

Given a grammar, valid sentences can be derived by repeated substitution.

Substitution

$$x + 2 - y$$

Expression grammar

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\begin{array}{llcl}
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Parser

Substitution

Given a grammar, valid sentences can be derived by repeated substitution.

Substitution

$$\begin{array}{ll} 5 & term \; + 2 - y \\ & x + 2 - y \end{array}$$

Expression grammar

$$\begin{array}{lrcl} 1 & goal & ::= & expr \\ 2 & expr & ::= & expr\ op\ term \\ 3 & & \mid & term \\ 4 & term & ::= & number \\ 5 & & \mid & id \\ 6 & op & ::= & + \\ 7 & & \mid & - \end{array}$$

Parser

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Substitution

6	
3	$expr \ + 2 - y$
5	$term \ + 2 - y$
	$x + 2 - y$

Expression grammar

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Parser

Substitution

Given a grammar, valid sentences can be derived by repeated substitution.

Substitution

1	$goal$
2	$expr$
5	$expr\ op\ term$
7	$expr\ op\ y$
2	$expr\ - y$
4	$expr\ op\ term\ - y$
6	$expr\ op\ 2 - y$
3	$expr\ + 2 - y$
5	$term\ + 2 - y$
	$x + 2 - y$

Expression grammar

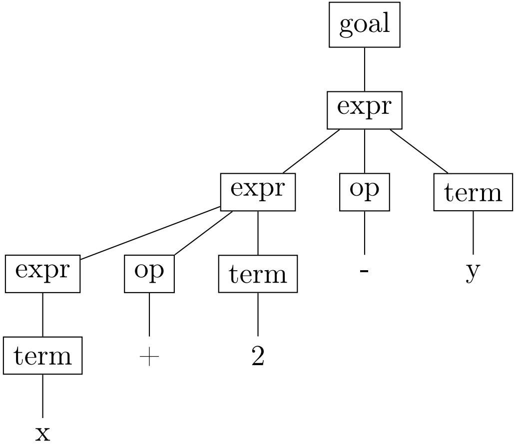
1	$goal$	$::=$	$expr$
2	$expr$	$::=$	$expr\ op\ term$
3		$\mid$	$term$
4	$term$	$::=$	$number$
5		$\mid$	id
6	op	$::=$	$+$
7		$\mid$	$-$

Parser

Parse tree

The result of a parse can be represented by a parse tree or syntax tree.

Parse tree



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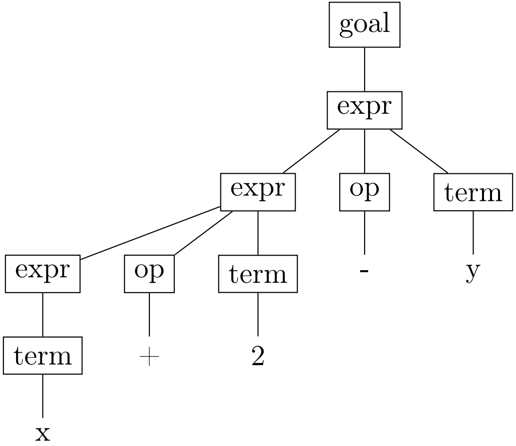
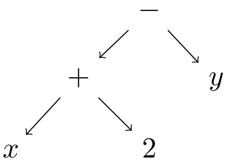


Abstract syntax tree



Middle end

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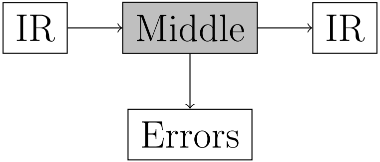

Duty of the middle end

- Semantic analyses
- Static analyses
- Typing
- Constant propagation, folding
- Common sub-expression elimination

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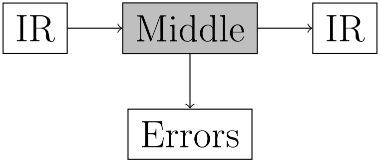

Duty of the middle end

- Semantic analyses
- Static analyses
- Typing
- Constant propagation, folding
- Common sub-expression elimination
- Redundant code elimination
- Dead code elimination
- Return path analysis
- ...

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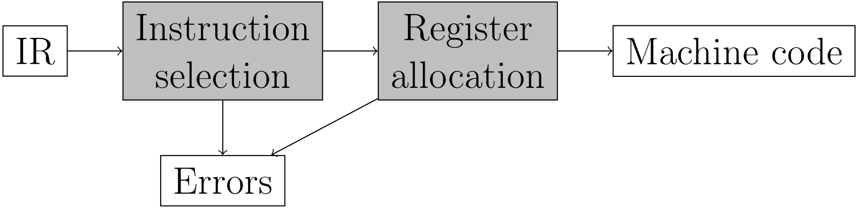
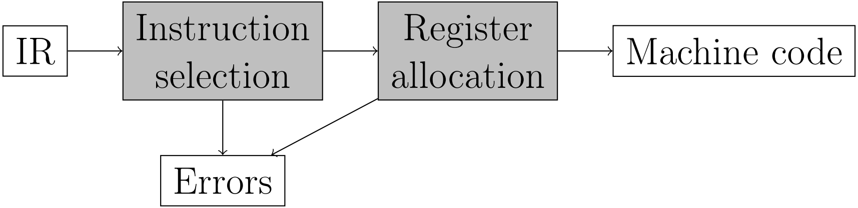
Backend


IR
Instruction selection
Register allocation
Machine code
Errors

Backend



Duty of the backend

- Translate the IR to machine code
- Decide what registers to use
- Ensure conformance with system interfaces

SPL

Simple Programming Language (SPL)

Properties

- Designed at UU

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- Pascal/C-like language

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- Incomplete specification
- Compilers will differ, examples may not always run

SPL Examples

Hello world!

```
main ( ) : Void {
  print ('H':'e':'l':'l':'o':' ':'w':'o':'r':'l':'d':'!':[]);
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With a mini extension:

```
main ( ) : Void {
  print ("Hello world!");
  print (42);
  print (True);
}
```

SPL Examples

Factorial

```
facR (n : Int) : Int {
  if (n < 0) {
    return 1;
  } else {
    return n * facR (n - 1);
  }
}
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SPL Examples

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```
facI (n) {
  var r = 1;
  while (n > 1) {
    r = r * n;
    n = n - 1;
  }
  return r;
}
```

SPL Examples

List examples

```
product ( list : [Int] ) : Int {
  if (isEmpty(list)) {
    return 1;
  } else {
    return list.hd
      * product (list.tl);
  }
}
```

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```
fromTo (from, to) {
  if (from <= to) {
    return from : fromTo (from+1,
   to);
  } else {
    return [];
  }
}
```

SPL Examples

Polymorphism

```
reverse ( list : [t] ) : [t] {
  var accu = [];
  while (isEmpty(list)) {
    accu = list.hd : accu;
    list = list.tl;
  }
  return accu;
}
```

Project

Compiler construction

6ECTS

Compiler construction

6ECTS

Compiler construction

6ECTS

In this course

Project information

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  - Simulator is provided
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- Four phases:
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  4. Extension
- Write up a report in every phase
- Deadlines are on brightspace
- Tested in an oral exam

In this course

Grading & Progress

- Mandatory to work in git (`https://gitlab.science.ru.nl/compilerconstruction`).

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  - `2425/`: Group containing your private repos Mart creates when the groups are known.

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- Done in groups of two.
- Every phase ends with a presentation and a report section.
- Every group presents one phase.
- Compiler extension is a case study.
- As soon as possible: Choose a partner and a language (brightspace group enroll).
- During the course: Think about a nice extension and discuss this with us.

Version control with git

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- If you want to understand it better:
  Git from the Bottom Up — John Wiegley:
  `https://jwiegley.github.io/git-from-the-bottom-up/`

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Take home

- Log in on gitlab.

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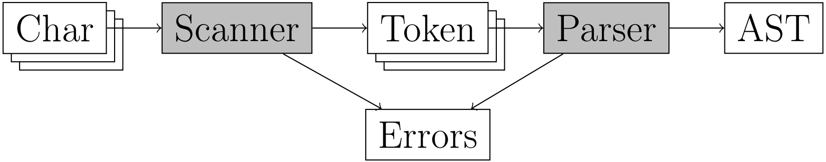
- N.B. The tutorial session is a Q&A session, send an email to register (`mart@cs.ru.nl`).

Part II

Scanners

Recap

Remember the frontend



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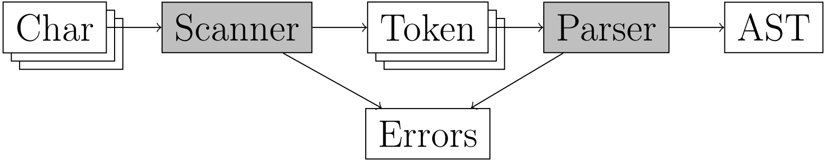

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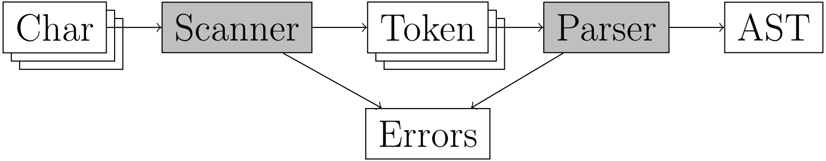

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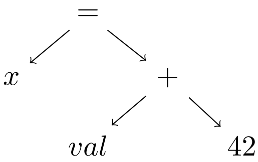

Scanner

Specifying allowed input

Allowed input

- Parser: CFG (sentences)
- Scanner: RE (words)

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Easy tokens

- Keywords: `case`, `if`, `module`, `while`
- Comments: anything after `//` or between `/*` and `*/`
- Whitespace

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- Comments: anything after `//` or between `/*` and `*/`
- Whitespace

Tricky tokens

- Integers: perhaps a sign followed by digits
- Decimal: integer followed by a `'.'`, scientific notation?
- Identifier: `'_'` or letter followed by letters, digits or `'_'`.
- Characters: Single character between single quotes, or an escape sequence.

Regular expressions

$$letter \quad ::= \quad a \mid b \mid \ \ldots \ \mid z \mid A \mid B \mid \ \ldots \ \mid Z$$

Regular expressions

$$
\begin{aligned}
\mathit{letter} \quad &::= \quad a \mid b \mid \ldots \mid z \mid A \mid B \mid \ldots \mid Z \\
\mathit{digit} \quad &::= \quad 0 \mid 1 \mid \ldots \mid 9
\end{aligned}
$$

Regular expressions

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Recognising regular expressions

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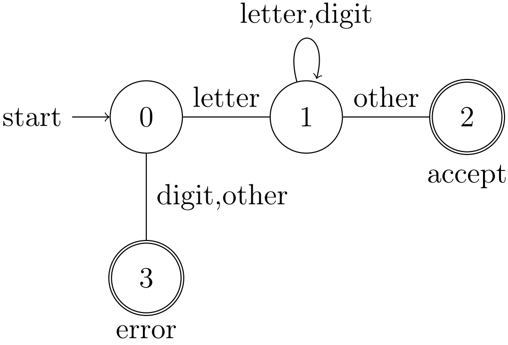

Haskell Example

Creating a lexer by hand

In Haskell: `scanner.hs`

```
data Token
    = MinusToken | PlusToken | TimesToken | DivideToken
    | BraceOpen | BraceClose
    | NumToken Integer | IdentToken String
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  deriving (Show, Eq)
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Recognising regular expressions

Haskell code: `scanner.hs` (2)

```
...

tokenise (c:xs)
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```

Recognising regular expressions

Haskell code: `scanner.hs` (2)

```
...

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```

Recognising regular expressions

Haskell code: `scanner.hs` (2)

```
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tokenise (c:xs)
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```

Recognising regular expressions

Haskell code: `scanner.hs` (2)

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    | otherwise = ErrToken ("Unrecognised character: " ++ show c) :
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```

Recognising regular expressions

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tokenise [] = []

spanToken :: (Char → Bool) → ([Char] → Token) → [Char] → [Token]
spanToken pred tfun cs = tfun tchars:tokenise rest
  where (tchars, rest) = span pred cs
```

C/C++ Example

Lexer generators

using (f)lex in C/C++

- Extra compilation step
  - `lex -t scanner.l > scanner.c`
  - `cc scanner.c -o scanner`
  - or use make.
- Generate efficient scanner code
- Generate an automaton as a jump table
- lex for C/C++, alex for Haskell, see: `https://en.wikipedia.org/wiki/Comparison_of_parser_generators#Regular_languages`

Lexer generators using (f)lex in C/C++

scanner.l

```
%{
#include <stdio.h>
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[ \n\t]         ; // eat whitespace
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```

Lexer generators using (f)lex in C/C++

`scanner.l`

```
%{
#include <stdio.h>
%}
%%
"//".*\n        printf("line comment\n");
[ \n\t]         ; // eat whitespace
\-              printf("minus\n");
"+"             printf("plus\n");
"*"             printf("times\n");
"/"             printf("divide\n");
"("             printf("brace open\n");
")"             printf("brace close\n");
```

Lexer generators using (f)lex in C/C++

scanner.l

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#include <stdio.h>
%}
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"//".*\n       printf("line comment\n");
[ \n\t]        ; // eat whitespace
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...
[+-]?[0-9]+    printf("number: %d\n", atoi(yytext));
[_a-zA-Z][_a-zA-Z0-9-]* printf("ident: %s\n", yytext);
```

Lexer generators using (f)lex in C/C++

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    yytext[0]);
```

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   yytext[0]);
%%
int main (void)
{
  return yylex();
}
```

Lexer generators using (f)lex in C/C++

`scanner.l` (2) Multiline comments

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%x IN_COMMENT
...
%%
<INITIAL>{
"/*"            BEGIN(IN_COMMENT);
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Lexer generators using (f)lex in C/C++

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}
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"*/"            BEGIN(INITIAL);
[^*\n]+         ; // eat comment in chunks
"*"             ; // eat the lone star
\n              yylineno++;
}
```

Conclusion

Scanners in practise

- Most languages have regular tokens.

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- Some deem lexers obsolete (lecture 3).
- Many languages have lexers written by hand
- Many languages use lexer generators
- There is such a thing as the Lexer hack (lecture 3)

Abstracter view of compilers (extra)

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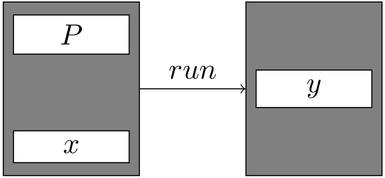

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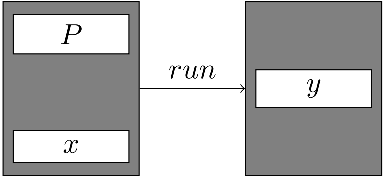

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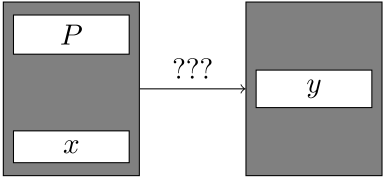
- General case?

Implementation (extra)

- An implementation of a language A is a method with which we can compute $[\![P]\!]^A(x)$ (for arbitrary P and x):



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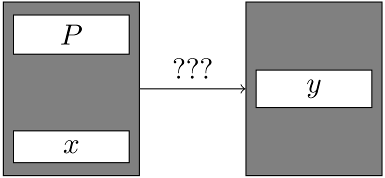

$$y = [\![P]\!]^A(x)$$

- We already have an implementation for a machine language. What to do with other languages?

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- A compiler from A to B (written in C) is a program F such that for any P and x

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- Notation: $F : A \xrightarrow{C} B$

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- We introduce a more concise notation

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- Applications associate to the left

$$F \underset{C}{\cdot} P \underset{B}{\cdot} x = (F \underset{C}{\cdot} P) \underset{B}{\cdot} x$$

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- We have a compiler F (in machine language) from Java to machine language

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$$\begin{aligned} P \underset{J}{\cdot} x &= (F \underset{M}{\cdot} P) \underset{M}{\cdot} x \\ &= (F \; ! \; P) \; ! \; x \end{aligned}$$

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- From this we know what we need to do:
  1. Load F as program, P as input
  2. Run
  3. Load the output from 2 as program, x as input
  4. Run

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- Wanted: an implementation B

$$P \underset{B}{\cdot} x \quad = G \underset{M}{\cdot} P \underset{A}{\cdot} x$$

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$$
\begin{aligned}
P \underset{B}{\cdot} x &= G \underset{M}{\cdot} P \underset{A}{\cdot} x \\
&= F \underset{M}{\cdot} (G \underset{M}{\cdot} P) \underset{M}{\cdot} x
\end{aligned}
$$

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  - a compiler G from B to A in A: $G : B \xrightarrow{A} A$

Example 3 (extra)

- We have
  - a compiler F from A to machine language in machine language: $F : A \overset{M}{\to} M$
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- Wanted: an implementation B

$$P \underset{B}{\cdot} x \quad = G \underset{A}{\cdot} P \underset{A}{\cdot} x$$

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$$\begin{aligned} P \underset{B}{\cdot} x &= G \underset{A}{\cdot} P \underset{A}{\cdot} x \\ &= F \,!\, G \,!\, P \underset{A}{\cdot} x \end{aligned}$$

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$$
\begin{aligned}
P \underset{B}{\cdot} x &= G \underset{A}{\cdot} P \underset{A}{\cdot} x \\
&= F \,!\, G \,!\, P \underset{A}{\cdot} x \\
&= F \,!\, (F \,!\, G \,!\, P) \,!\, x
\end{aligned}
$$

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- Take a good look again: which run occurs when?

Efficiency (extra)

- We have

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  - a compiler F from J to M in M ($F : J \stackrel{M}{\to} M$)

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Efficiency (extra)

- We have
  - a compiler F from J to M in M ($F : J \overset{M}{\to} M$)
  - a compiler G from J to M in J ($G : J \overset{J}{\to} M$)
- Wanted: an implementation of J
- Include efficiency information: M^+, M^-

Efficiency (extra)

- We have
  - a compiler F from J to M in M ($F : J \xrightarrow{M} M$)
  - a compiler G from J to M in J ($G : J \xrightarrow{J} M$)
- Wanted: an implementation of J
- Include efficiency information: M^+, M^-
  - a compiler F from J to M^- in M ($F : J \xrightarrow{M^-} M^-$)

Efficiency (extra)

- We have
  - a compiler F from J to M in M ($F : J \xrightarrow{M} M$)
  - a compiler G from J to M in J ($G : J \xrightarrow{J} M$)
- Wanted: an implementation of J
- Include efficiency information: M^+, M^-
  - a compiler F from J to M^- in M ($F : J \xrightarrow{M^-} M^-$)
  - a compiler G from J to M^+ in J ($G : J \xrightarrow{J} M^+$)

Solutions (extra)

Remember our compilers

$$F : J \xrightarrow{M^-} M^- \quad G : J \xrightarrow{J} M^+$$

Solutions (extra)

Remember our compilers

$$F : J \overset{M^-}{\rightarrow} M^- \quad G : J \overset{J}{\rightarrow} M^+$$

Solution 1

- Use only F

$$P \underset{J}{\cdot} x = (F \; !^- \; P) \; !^- \; x$$

Solutions (extra)

Remember our compilers

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Solution 1

- Use only F

$$P \underset{J}{\cdot} x = (F \,!^-\, P) \,!^-\, x$$

- Two inefficient runs for each P and x

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$$P \underset{J}{\cdot} x = (F \;!^-\; P) \;!^-\; x$$

- Two inefficient runs for each P and x

Solution 2

- Note that

$$F \;!^-\; G : J \xrightarrow{M^-} M^+$$

Solutions (extra)

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$$F : J \overset{M^-}{\to} M^- \quad G : J \overset{J}{\to} M^+$$

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- Use only F

$$P \underset{J}{\cdot} x = (F \,!^-\, P) \,!^-\, x$$

- Two inefficient runs for each P and x

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- Thus

$$P \underset{J}{\cdot} x = (F \,!^-\, G) \,!^-\, P \,!^+\, x$$

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Solutions (extra)

Remember our compilers

$$F : J \xrightarrow{M^-} M^- \qquad G : J \xrightarrow{J} M^+$$

- Idea

$$G \underset{J}{\cdot} G : J \xrightarrow{M^+} M^+$$

Solutions (extra)

Remember our compilers

$$F : J \overset{M^-}{\rightarrow} M^- \quad G : J \overset{J}{\rightarrow} M^+$$

- Idea

$$G \underset{J}{\cdot} G : J \overset{M^+}{\rightarrow} M^+$$

- Thus

$$P \underset{J}{\cdot} x \quad = (G \underset{J}{\cdot} G) \; !^+ \; P \; !^+ \; x$$

Solutions (extra)

Remember our compilers

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$$G \underset{J}{\cdot} G : J \overset{M^+}{\to} M^+$$

- Thus

$$\begin{aligned} P \underset{J}{\cdot} x &= (G \underset{J}{\cdot} G) \,!^+\, P \,!^+\, x \\ &= ((F \,!^-\, G) \,!^-\, G) \,!^+\, P \,!^+\, x \end{aligned}$$

Solutions (extra)

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Recipe

1. run G with F: inefficient G
2. run G with inefficient G: efficient G
3. run P with G
4. run P with x

Solutions (extra)

Remember our compilers

$$F : J \overset{M^-}{\rightarrow} M^- \quad G : J \overset{J}{\rightarrow} M^+$$

- Idea

$$G \underset{J}{\cdot} G : J \overset{M^+}{\rightarrow} M^+$$

- Thus

$$\begin{aligned} P \underset{J}{\cdot} x &= (G \underset{J}{\cdot} G) \,!^+\, P \,!^+\, x \\ &= ((F \,!^-\, G) \,!^-\, G) \,!^+\, P \,!^+\, x \end{aligned}$$

Recipe

1. run G with F: inefficient G
2. run G with inefficient G: efficient G
3. run P with G
4. run P with x

- Inefficient just runs once
- F is needed once:

Solutions (extra)

Remember our compilers

$$F : J \stackrel{M^-}{\to} M^- \quad G : J \stackrel{J}{\to} M^+$$

- Idea

$$G \underset{J}{\cdot} G : J \stackrel{M^+}{\to} M^+$$

- Thus

$$\begin{aligned} P \underset{J}{\cdot} x &= (G \underset{J}{\cdot} G)\ !^+\ P\ !^+\ x \\ &= ((F\ !^-\ G)\ !^-\ G)\ !^+\ P\ !^+\ x \end{aligned}$$

Recipe

1. run G with F: inefficient G
2. run G with inefficient G: efficient G
3. run P with G
4. run P with x

- Inefficient just runs once
- F is needed once: bootstrapping

Bootstrapping in real life

GCC

- hex0
- hex1
- hex2
- cc_x86
- M2-planet
- mes (mescc)
- tinycc
- ...
- tinycc
- gcc (musl)
- gcc
- gcc
- ...
- gcc

`https://bootstrappable.org/`

Take home

- Log in on gitlab.
- Enroll for a group.
- Check the schedule *Contents*→*Overview*.
- In case of questions/ideas/wishes
  don't hesitate to contact us.
- N.B. The tutorial session is a Q&A session, send an email to register (`mart@cs.ru.nl`).
- What to do with the practical session?