Compilerconstructie

najaar 2019

`http://www.liacs.leidenuniv.nl/~vlietrvan1/coco/`

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college 1, vrijdag 6 september 2019

Overview

Why this course

It's part of the general background of a software engineer

- How do compilers work?
- How do computers work?
- What machine code is generated for certain language constructs?
- Working on a non-trivial programming project

After the course

- Know how to build a compiler for a simplified progr. language
- Know how to use compiler construction tools, such as generators for scanners and parsers
- Be familiar with compiler analysis and optimization techniques

Prior Knowledge

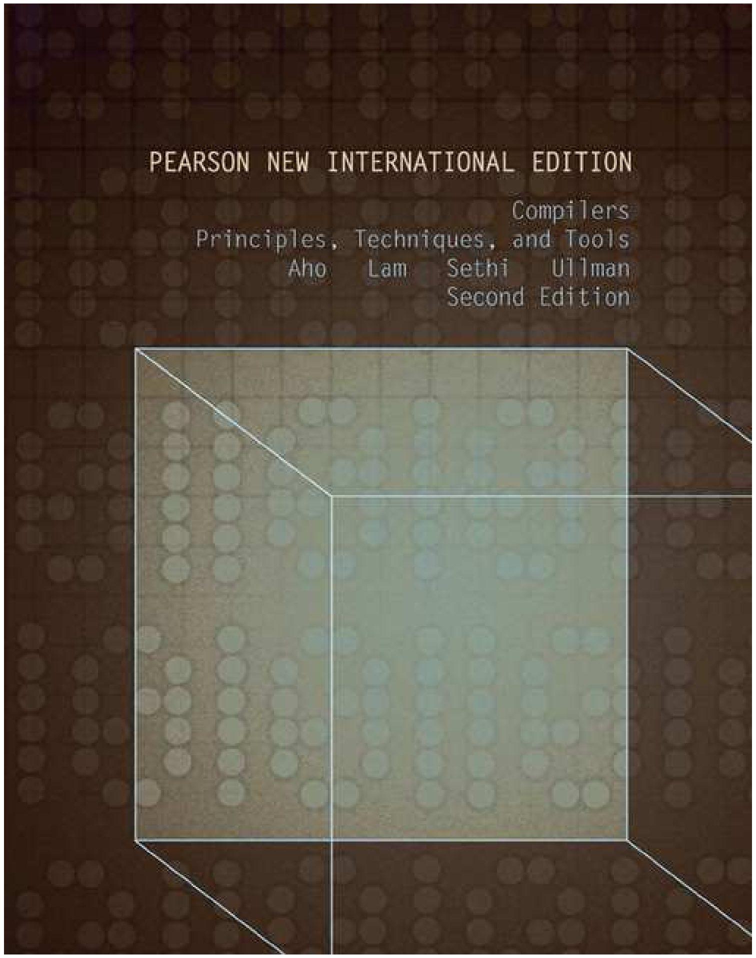
(mag ik dit nog zeggen?)

- Algoritmiek

- Fundamentele Informatica 2

Course Outline

- In class, we discuss the theory using the ‘dragon book’ by Aho et al.
- The theory is applied in the practicum to build a compiler that converts Pascal code to MIPS instructions.


PEARSON NEW INTERNATIONAL EDITION
Compilers
Principles, Techniques, and Tools
Aho Lam Sethi Ullman
Second Edition

A.V. Aho, M.S. Lam, R. Sethi, and J.D. Ullman,
Compilers: Principles, Techniques, and Tools (second edition),
Pearson, 2013, ISBN: 978-1-29202-434-9 (international edition).

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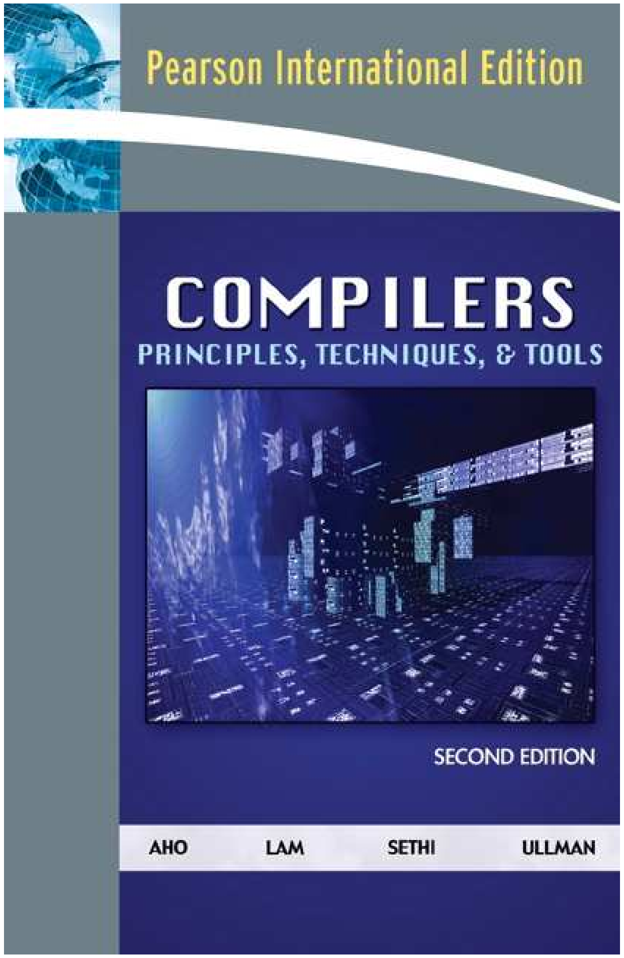
Pearson International Edition
COMPILERS
PRINCIPLES, TECHNIQUES, & TOOLS
SECOND EDITION
AHO
LAM
SETHI
ULLMAN

A.V. Aho, M.S. Lam, R. Sethi, and J.D. Ullman,
Compilers: Principles, Techniques, & Tools (second edition),
Pearson, 2007, ISBN: 978-0-321-49169-5 (international edition).

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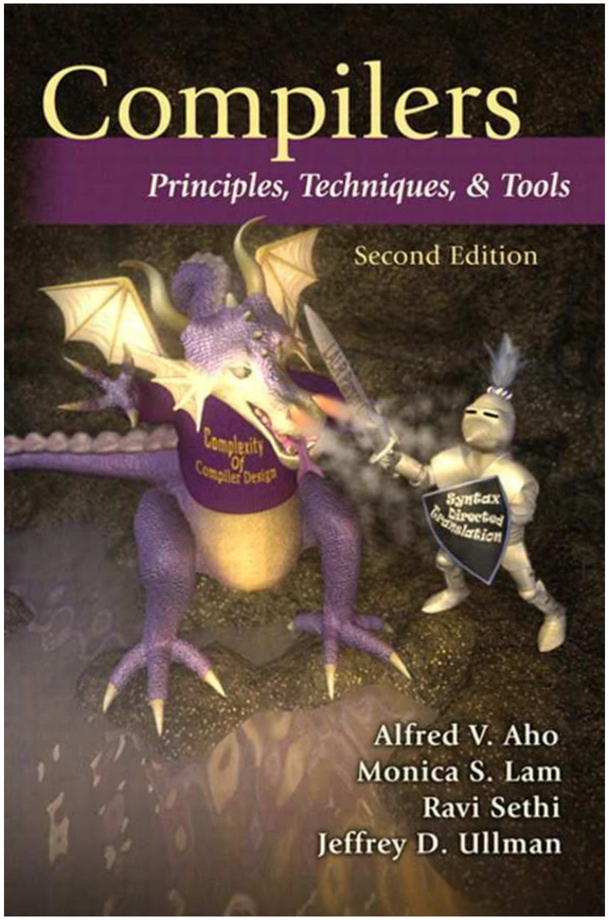
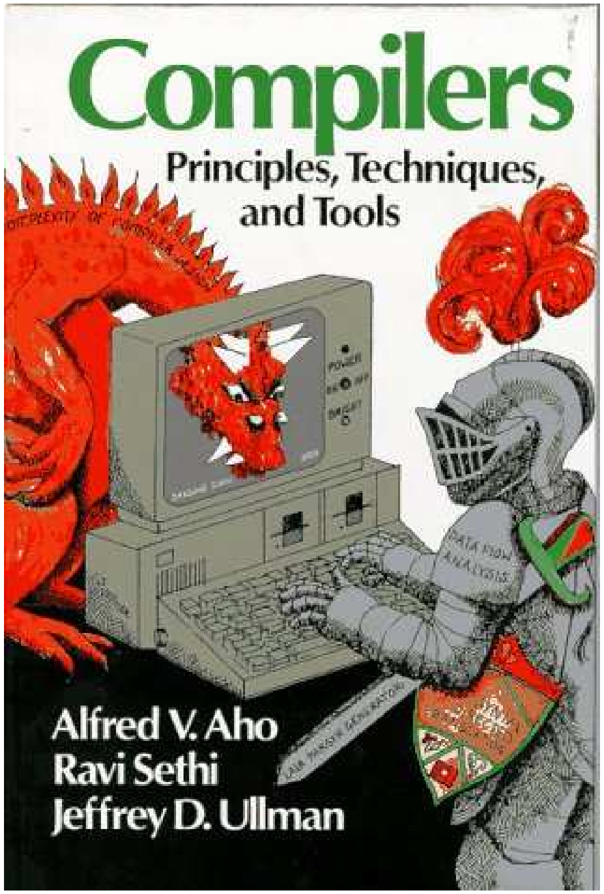

Compilers
Principles, Techniques, & Tools
Second Edition
Complexity of Compiler Design
Syntax Directed Translation
Alfred V. Aho
Monica S. Lam
Ravi Sethi
Jeffrey D. Ullman

A.V. Aho, M.S. Lam, R. Sethi, and J.D. Ullman,
Compilers: Principles, Techniques, & Tools (second edition),
Pearson, 2006, ISBN: 978-0321486813

Earlier edition

- Dragon book has been revised in 2006
- In Second edition good improvements are made
  - Parallelism
    - * . . .
    - * Array data-dependence analysis
- First edition may also be used, but not recommended



A.V. Aho, R. Sethi, and J.D. Ullman, *Compilers: Principles, Techniques, and Tools*, Addison-Wesley, 1986, ISBN-10: 0-201-10088-6 / 0-201-10194-7 (international edition).

Course Outline

- Contact
  - Room 140, tel. 071-5272876, rvvliet(at)liacs(dot)nl
  - Course website:
    `http://www.liacs.leidenuniv.nl/~vlietrvan1/coco/`
    Lecture slides, assignments
  - Grades on Blackboard

- Practicum
  - 4 self-contained assignments
  - Teams of two students
  - Assignments are submitted by e-mail
  - Assistant: Rintse van de Vlasakker

- Written exam
  - 19 December 2019, 14:00–17:00
  - 23 January 2020, 14:00–17:00

Course Outline

- You need to pass all 4 assignments and the written exam to obtain a sufficient grade
- Then, you obtain 6 EC
- Algorithm to compute final grade:

```
if (E >= 5.5)
{ if (A2,A3,A4 >= 5.5)
  { P = (A2+A3+A4)/3;
    F = (E+P)/2;
  }
  else
    F is undefined;
}
else
  F = E;
```

Studying only from the lecture slides may not be sufficient. Relevant book chapters will be given.

Course Outline

(tentative)

1. Overview
2. Symbol Table / Lexical Analysis
3. Syntax Analysis 1 (+ exercise class)
4. Syntax Analysis 2 (+ exercise class)
   Assignment 1
6. Static Type Checking
7. Assignment 2
8. Intermediate Code Generation 1 (+ lab session . . .)
9. Intermediate Code Generation 2 (+ exercise class)
10. Assignment 3
11. Storage Organization and Code Generation
    (+ exercise class + lab session . . .)
12. Code optimization 1 (+ exercise class)
13. Assignment 4
14. Code Optimization 2 (+ exercise class + lab session . . .)

Practicum

- Assignment 1: Calculator
- Assignment 2: Parsing & Syntax tree
- Assignment 3: Intermediate code
- Assignment 4: Assembly generation

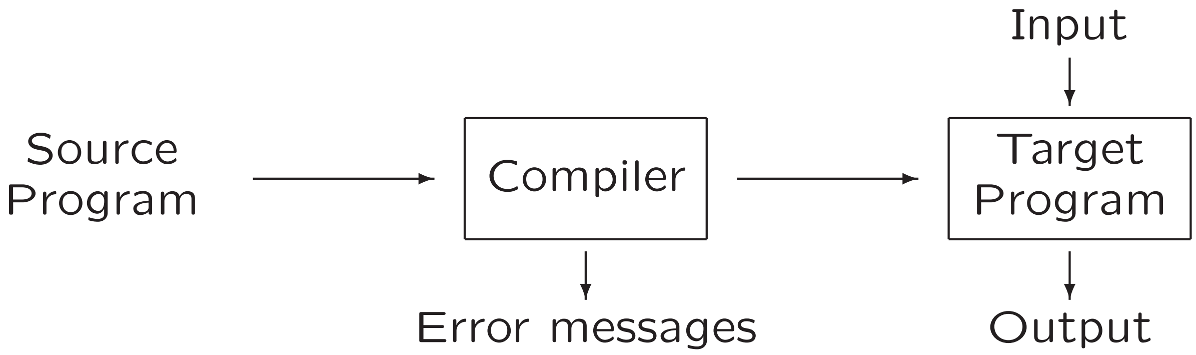
2×2 academic hours of Lab session + 3 weeks to complete (except assignment 1)

Strict deadlines (with one second chance)

1.1 Language Processors

- Compilation:

  Translation of a program written in a source language into a semantically equivalent program written in a target language



Input

Source Program

Compiler

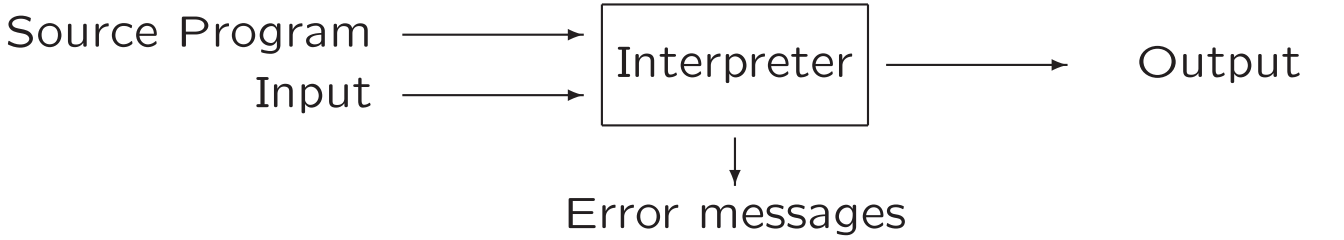
Target Program

Error messages

Output

- Interpretation:

  Performing the operations implied by the source program.



Source Program

Input

Interpreter

Output

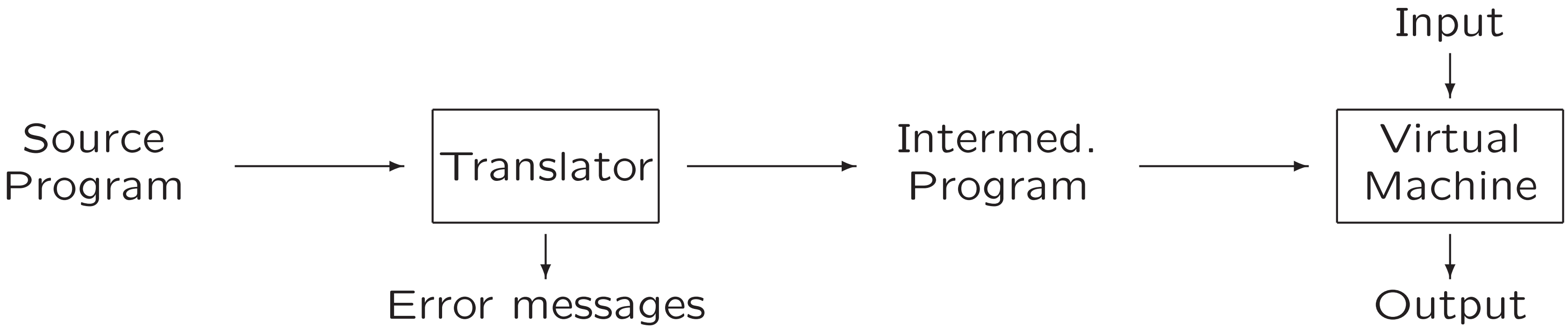
Error messages

Compilers and Interpreters

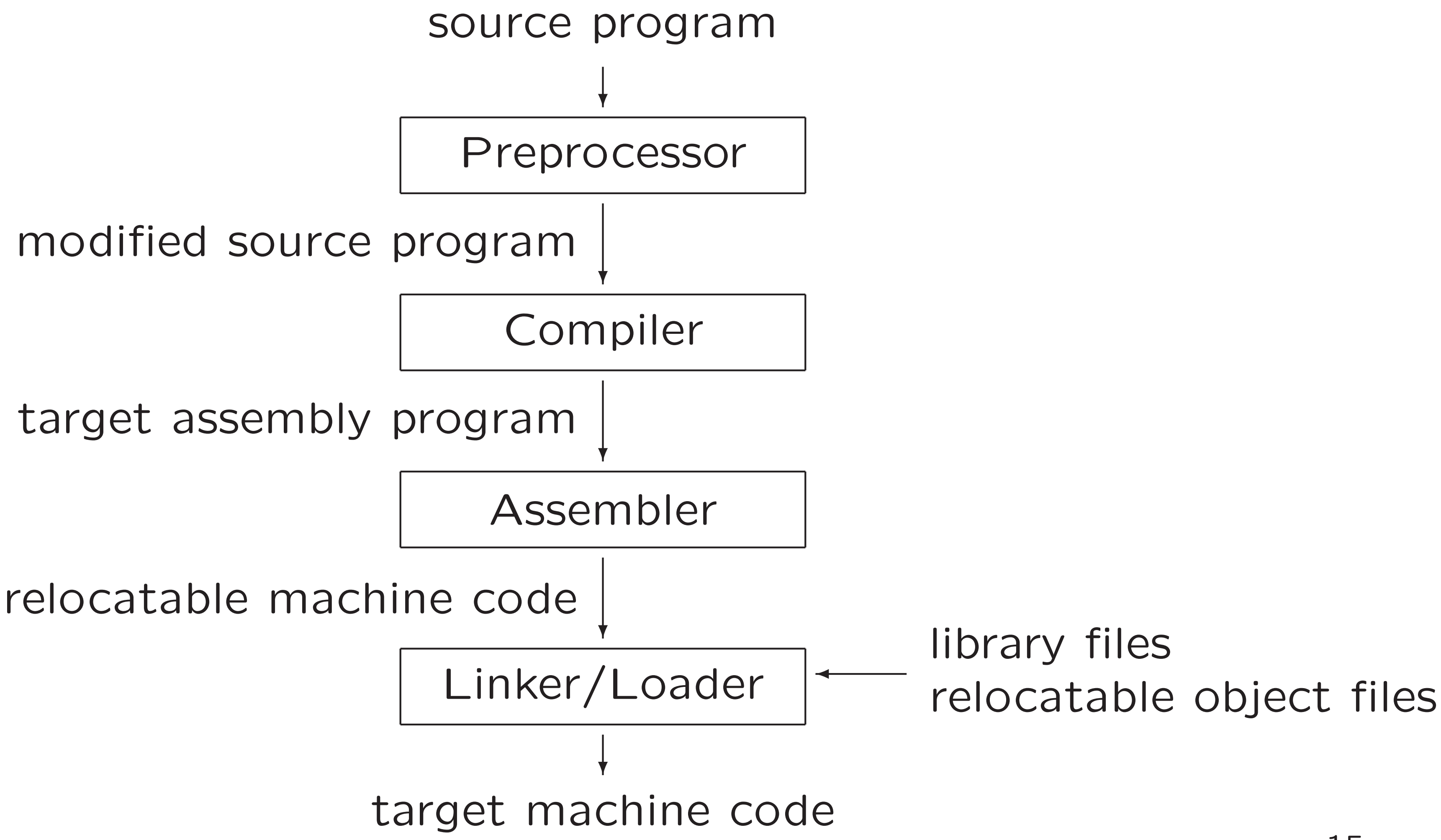
- Compiler: Translates source code into machine code, with scanner, parser, . . . , code generator
- Interpreter: Executes source code ‘directly’, with scanner, parser
  Statements in, e.g., a loop are scanned and parsed again and again

Compilers and Interpreters

- Hybrid compiler (Java):
  - Translation of a program written in a source language into a semantically equivalent program written in an intermediate language (bytecode)
  - Interpretation of intermediate program by virtual machine, which simulates physical machine



Compilation flow



source program

Preprocessor

modified source program

Compiler

target assembly program

Assembler

relocatable machine code

Linker/Loader

library files
relocatable object files

target machine code

1.2 The Structure of a Compiler

Analysis-Synthesis Model

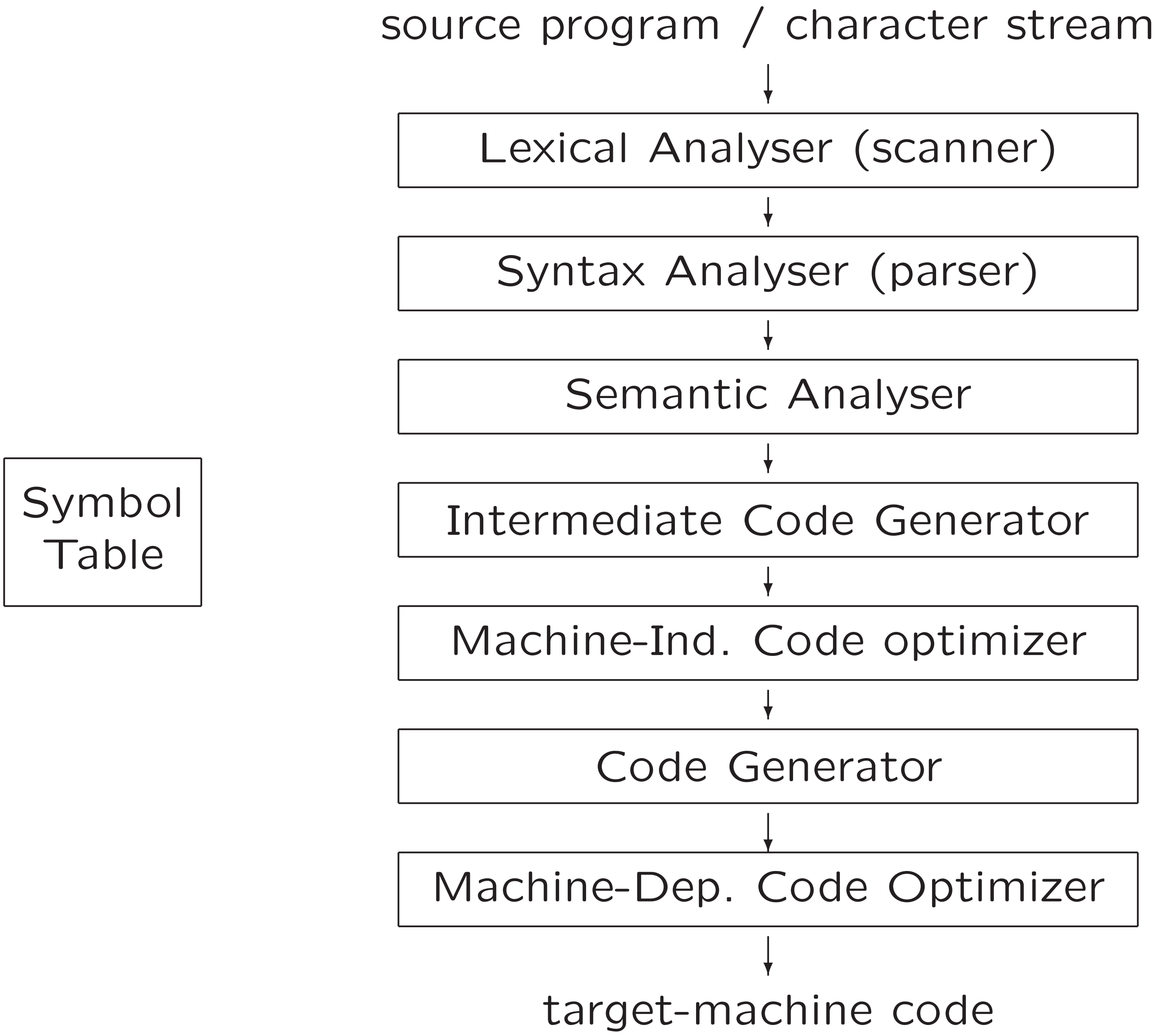
There are two parts to compilation:

- Analysis (front end)
  - Determines the operations implied by the source program which are recorded in an intermediate representation, e.g., a tree structure

- Synthesis (back end)
  - Takes the intermediate representation and translates the operations therein into the target program

Cf. editors with syntax highlighting or text auto completion

The Phases of a Compiler



source program / character stream

Lexical Analyser (scanner)

Syntax Analyser (parser)

Semantic Analyser

Symbol Table

Intermediate Code Generator

Machine-Ind. Code optimizer

Code Generator

Machine-Dep. Code Optimizer

target-machine code

The Phases of a Compiler

Character stream:

```
  position = initial + rate * 60
```

Lexical Analyser (scanner)

Token stream:

$$\langle \mathbf{id}, 1\rangle \ \langle = \rangle \ \langle \mathbf{id}, 2\rangle \ \langle + \rangle \ \langle \mathbf{id}, 3\rangle \ \langle * \rangle \ \langle \mathbf{num}, 60\rangle$$

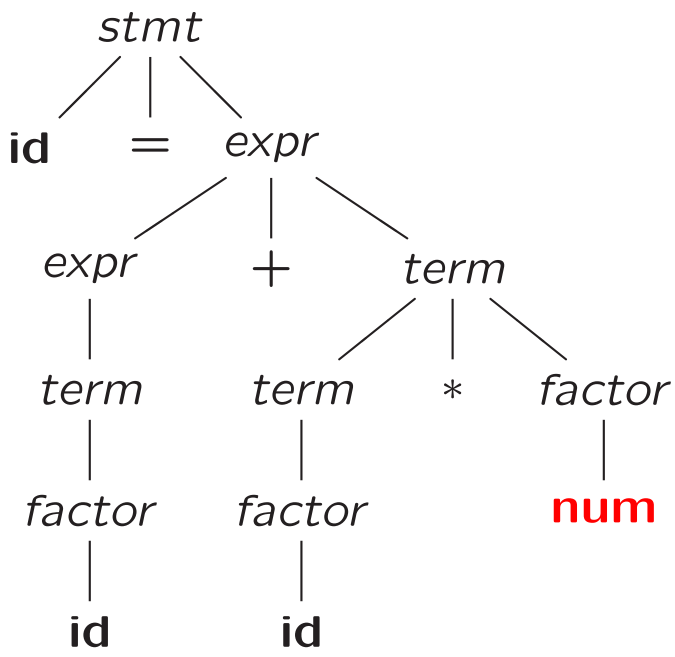
The Phases of a Compiler

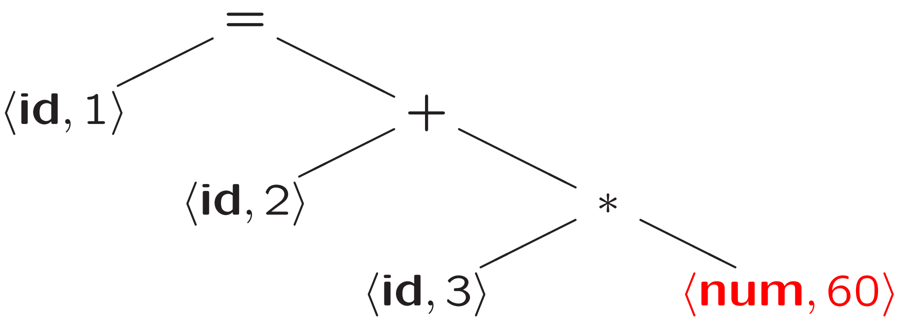
Token stream:

$$\langle \textbf{id}, 1\rangle \ \langle = \rangle \ \langle \textbf{id}, 2\rangle \ \langle + \rangle \ \langle \textbf{id}, 3\rangle \ \langle * \rangle \ \langle \textbf{num}, 60\rangle$$

Syntax Analyser (parser)

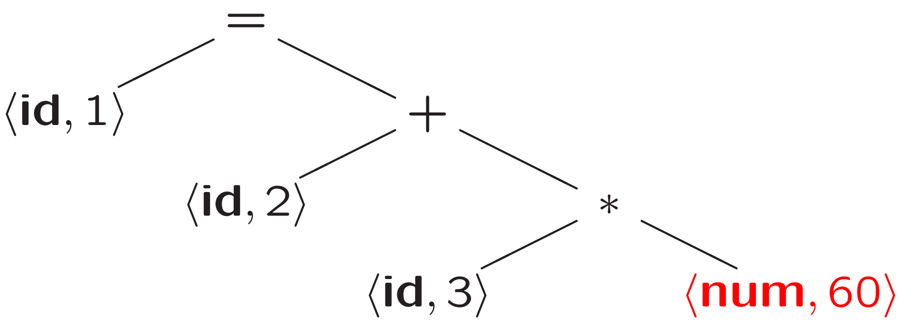
Parse tree / syntax tree:





The Phases of a Compiler

Syntax tree:

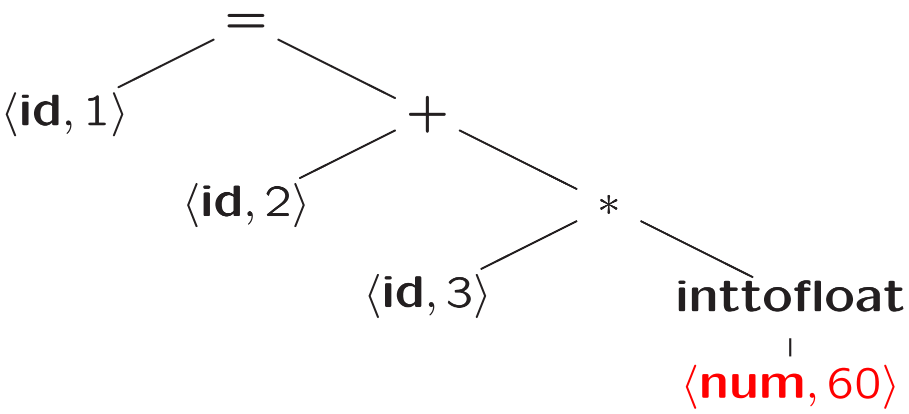


Semantic Analyser

Coercion

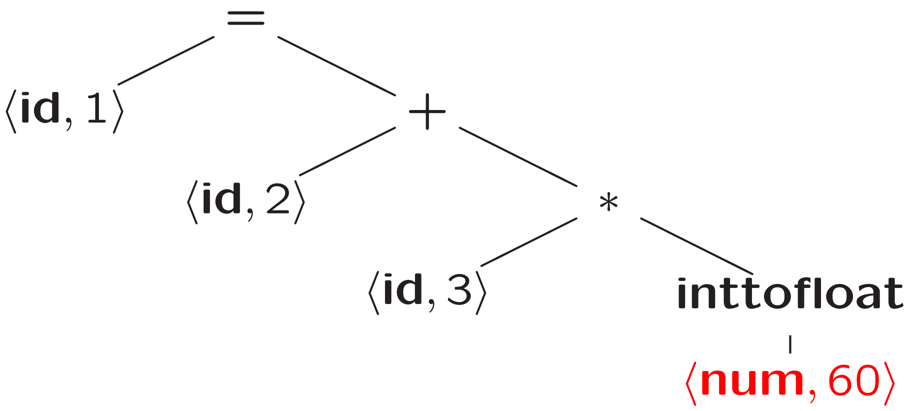
A[i], int x, break, . . .

Syntax tree:



The Phases of a Compiler

Syntax tree:



Intermediate Code Generator

One operator, explicit order

Temporary variables

Less than three operands

Intermediate code (three-address code):

```
t1 = inttofloat(60)
t2 = id3 * t1
t3 = id2 + t2
id1 = t3
```

The Phases of a Compiler

Intermediate code (three-address code):

```
t1 = inttofloat(60)
t2 = id3 * t1
t3 = id2 + t2
id1 = t3
```

Code Optimizer

Intermediate code (three-address code):

```
t1 = id3 * 60.0
id1 = id2 + t1
```

The Phases of a Compiler

Intermediate code (three-address code):

```
t1 = id3 * 60.0
id1 = id2 + t1
```

Code Generator

Target code (assembly code):

```
LDF  R2, id3
MULF R2, R2, #60.0
LDF  R1, id2
ADDF R1, R1, R2
STF  id1, R1
```

The Grouping of Phases

Phases constitute logical organization of compiler

Inefficient as implementation:

characters → $\boxed{\text{Scanner}}$ → tokens → $\boxed{\text{Parser}}$ → tree
→ $\boxed{\text{Semantic analyser}}$ → . . . → code

Phases are separate 'programs', which run sequentially
Each phase reads from a file and writes to a new file.

The Grouping of Phases

Other extreme: single-pass compiler

```
do
  scan token
  parse token
  check token
  generate code for token
while (not eof)
```

Phases work in an interleaved way
Portion of code is generated while reading portion of source program

Nowadays: often two-pass compiler

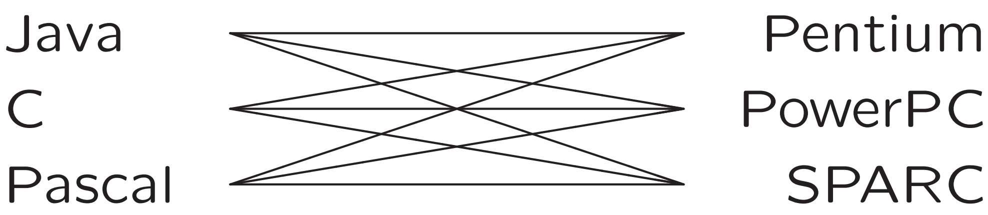
1.2.8 The Grouping of Phases

- Front End:
  scanning, parsing, semantic analysis, intermediate code generation
  (source code → intermediate representation)

- (optional) machine independent code optimization

- Back End:
  code generation, machine dependent code optimization
  (intermediate representation → target machine code)

language-dependent **machine-dependent**



Java
C
Pascal

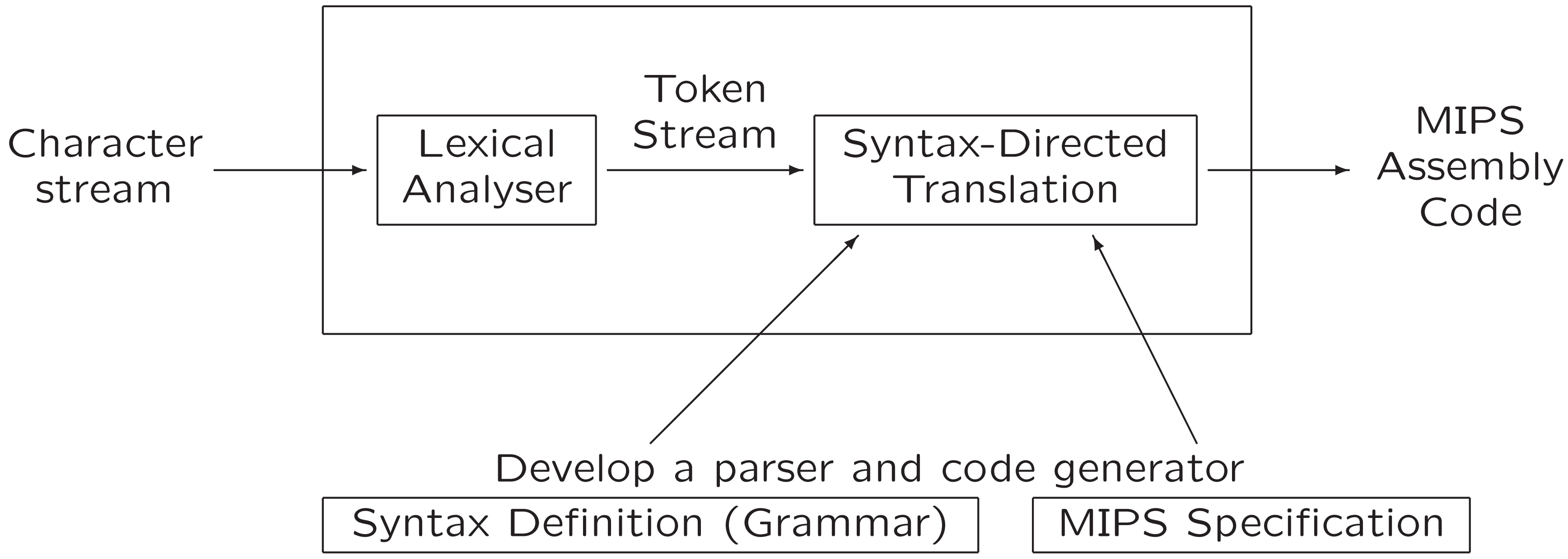
Pentium
PowerPC
SPARC

1.2.9 Compiler-Construction Tools

Software development tools are available to implement one or more compiler phases

- Scanner generators
- Parser generators
- Syntax-directed translation engines
- Code generator generators
- Data-flow analysis engines

The Structure of our compiler


Character stream
Lexical Analyser
Token Stream
Syntax-Directed Translation
MIPS Assembly Code
Develop a parser and code generator
Syntax Definition (Grammar)
MIPS Specification

Syntax-directed translation:
Using the syntactic structure of the language to generate output corresponding to some input

2.2 Syntax Definition

Context-free grammar is a 4-tuple with

- A set of *nonterminals* (syntactic variables)
- A set of *terminal* symbols (tokens)
- A designated *start* symbol (nonterminal)
- A set of *productions*: rules how to decompose nonterminals

Example: Context-free grammar for simple expressions:

$$G = (\{\mathit{list}, \mathit{digit}\},\ \{+, -, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}, \mathit{list},\ P)$$

with productions P:

$$\begin{array}{rcl} \mathit{list} & \rightarrow & \mathit{list} + \mathit{digit} \\ \mathit{list} & \rightarrow & \mathit{list} - \mathit{digit} \\ \mathit{list} & \rightarrow & \mathit{digit} \\ \mathit{digit} & \rightarrow & 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9 \end{array}$$

Derivation

Given a context-free grammar, we can determine the set of all strings (sequences of tokens) generated by the grammar using derivations:

- We begin with the start symbol

- In each step, we replace one nonterminal in the current form with one of the right-hand sides of a production for that nonterminal

Derivation (Example)

$$\begin{aligned} G &= (\{\mathit{list}, \mathit{digit}\},\ \{+, -, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}, \mathit{list},\ P) \\ & \quad \mathit{list} \rightarrow \mathit{list} + \mathit{digit} \mid \mathit{list} - \mathit{digit} \mid \mathit{digit} \\ & \quad \mathit{digit} \rightarrow 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9 \end{aligned}$$

Example: 9-5+2

$$\begin{aligned} \underline{\mathit{list}} &\Rightarrow \underline{\mathit{list}} + \mathit{digit} \\ &\Rightarrow \underline{\mathit{list}} - \mathit{digit} + \mathit{digit} \\ &\Rightarrow \underline{\mathit{digit}} - \mathit{digit} + \mathit{digit} \\ &\Rightarrow 9 - \underline{\mathit{digit}} + \mathit{digit} \\ &\Rightarrow 9 - 5 + \underline{\mathit{digit}} \\ &\Rightarrow 9 - 5 + 2 \end{aligned}$$

This is an example of leftmost derivation, because we replaced the leftmost nonterminal (underlined) in each step

Parse Tree

(derivation tree in FI2)

- The root of the tree is labelled by the start symbol

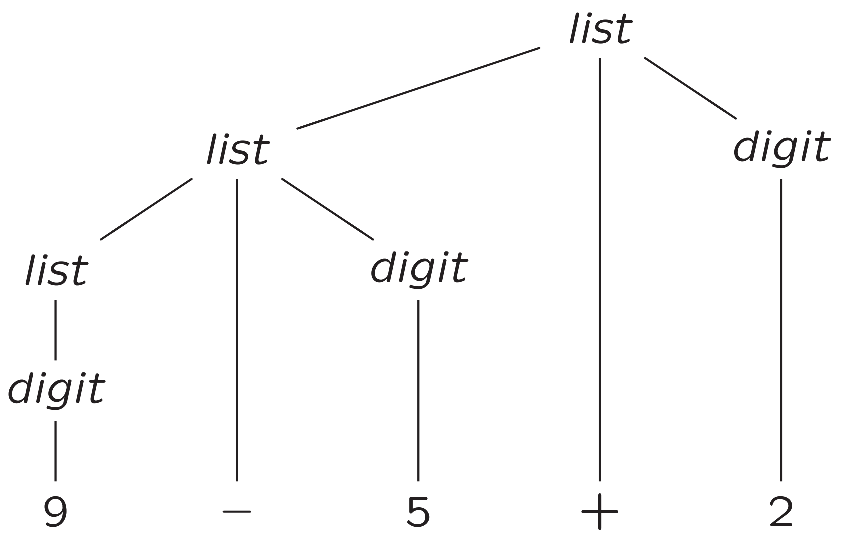
- Each leaf of the tree is labelled by a terminal (=token) or ϵ (=empty)

- Each interior node is labelled by a nonterminal

- If node A has children $X_1, X_2, \ldots, X_n$, then there must be a production $A \to X_1 X_2 \ldots X_n$

Parse Tree (Example)

Parse tree of the string $9 - 5 + 2$ using grammar G



Yield of the parse tree: the sequence of leafs (left to right)

Parsing: the process of finding a parse tree for a given string

Language: the set of strings that can be generated by some parse tree

Ambiguity

Consider the following context-free grammar:

$$G' = (\{\textit{string}\},\ \{+, -, 0, 1, 2, 3, 4, 5, 6, 7, 8, 9\}, \textit{string},\ P)$$

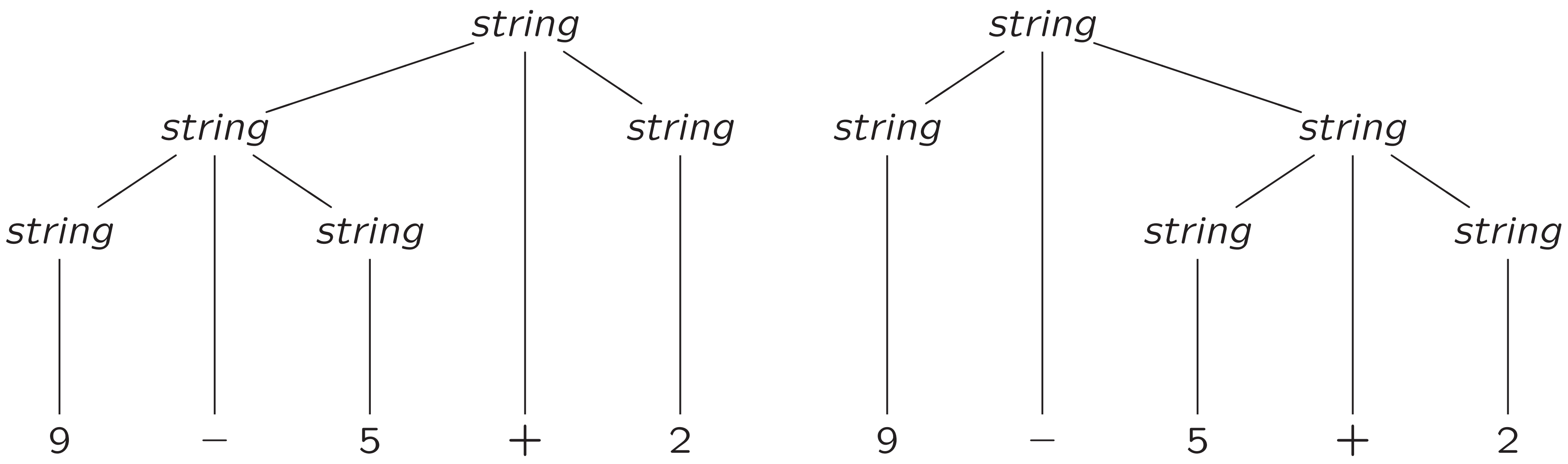
with productions P

$$\textit{string} \rightarrow \textit{string} + \textit{string} \mid \textit{string} - \textit{string} \mid 0 \mid 1 \mid \ldots \mid 9$$

This grammar is ambiguous, because more than one parse tree generates the string $9 - 5 + 2$

Ambiguity (Example)

Parse trees of the string $9 - 5 + 2$ using grammar G'



$(9 - 5) + 2 = 6$

$9 - (5 + 2) = 2$

Preferred. . .

Associativity of Operators

By convention

$$\left.\begin{array}{rcl} 9+5+2 & = & (9+5)+2 \\ 9-5-2 & = & (9-5)-2 \end{array}\right\} \text{left associative}$$

In most programming languages:

$+, -, *, /$ are left associative

$**, =$ are right associative:

$$\begin{array}{rcl} a**b**c & = & a**(b**c) \\ a=b=c & = & a=(b=c) \end{array}$$

Precedence of Operators

Consider: $9 + 5 * 2$

Is this $(9 + 5) * 2$ or $9 + (5 * 2)$?

Associativity does not resolve this

Precedence of operators:
$$\begin{array}{c} + \;\; - \\ * \;\; / \end{array} \Bigg\downarrow \begin{array}{l} \text{increasing} \\ \text{precedence} \end{array}$$

Unambiguous grammar for arithmetic expressions: . . .

Example:

$$9 + 5 * 2 * 3 + 1 + 4 * 7$$

Precedence of Operators

Consider: $9 + 5 * 2$
Is this $(9 + 5) * 2$ or $9 + (5 * 2)$?
Associativity does not resolve this

Precedence of operators: $\begin{array}{cc} + & - \\ * & / \end{array} \Big\downarrow$ increasing precedence

Unambiguous grammar for arithmetic expressions:

$$\begin{array}{rcl} \mathit{expr} & \to & \mathit{expr} + \mathit{term} \mid \mathit{expr} - \mathit{term} \mid \mathit{term} \\ \mathit{term} & \to & \mathit{term} * \mathit{factor} \mid \mathit{term} / \mathit{factor} \mid \mathit{factor} \\ \mathit{factor} & \to & \mathit{digit} \mid (\mathit{expr}) \\ \mathit{digit} & \to & 0 \mid 1 \mid \ldots \mid 9 \end{array}$$

Parse tree for $9 + 5 * 2$ . . .

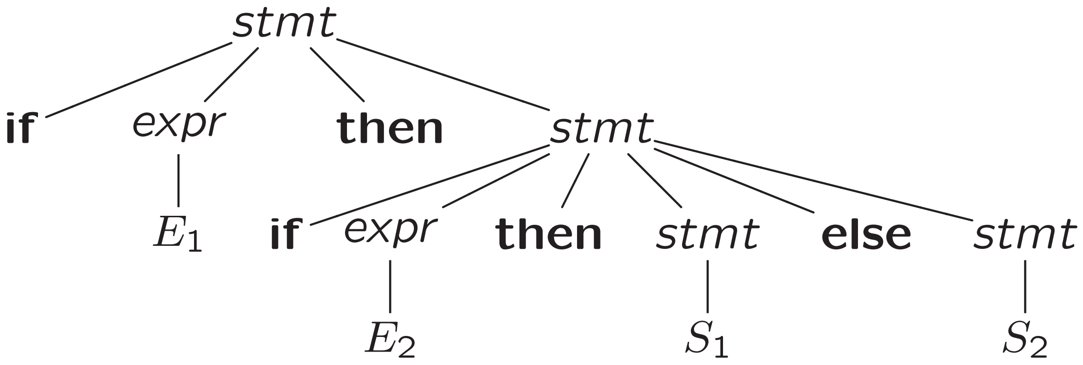
4.3.2 Eliminating ambiguity

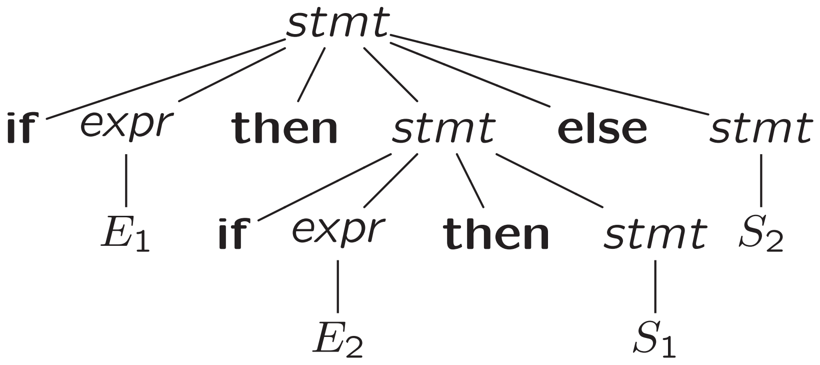
- Sometimes ambiguity can be eliminated
- Example: "dangling-else"-grammar

$$\begin{array}{rcl} \textit{stmt} & \rightarrow & \textbf{if}\ \textit{expr}\ \textbf{then}\ \textit{stmt} \\ & | & \textbf{if}\ \textit{expr}\ \textbf{then}\ \textit{stmt}\ \textbf{else}\ \textit{stmt} \\ & | & \textbf{other} \end{array}$$

Here, **other** is any other statement

if E_1 **then if** E_2 **then** S_1 **else** S_2





Preferred. . .

Eliminating ambiguity

Example: ambiguous “dangling-else”-grammar

$$\begin{array}{lcl} \textit{stmt} & \rightarrow & \textbf{if } \textit{expr} \textbf{ then } \textit{stmt} \\ & \mid & \textbf{if } \textit{expr} \textbf{ then } \textit{stmt} \textbf{ else } \textit{stmt} \\ & \mid & \textbf{other} \end{array}$$

Only matched statements between **then** and **else**...

Eliminating ambiguity

Example: ambiguous “dangling-else”-grammar

$$\begin{array}{rcl} \textit{stmt} & \rightarrow & \textbf{if } \textit{expr } \textbf{then } \textit{stmt} \\ & \mid & \textbf{if } \textit{expr } \textbf{then } \textit{stmt } \textbf{else } \textit{stmt} \\ & \mid & \textbf{other} \end{array}$$

Equivalent unambiguous grammar

$$\begin{array}{rcl} \textit{stmt} & \rightarrow & \textit{matchedstmt} \\ & \mid & \textit{openstmt} \\ \textit{matchedstmt} & \rightarrow & \textbf{if } \textit{expr } \textbf{then } \textit{matchedstmt } \textbf{else } \textit{matchedstmt} \\ & \mid & \textbf{other} \\ \textit{openstmt} & \rightarrow & \textbf{if } \textit{expr } \textbf{then } \textit{stmt} \\ & \mid & \textbf{if } \textit{expr } \textbf{then } \textit{matchedstmt } \textbf{else } \textit{openstmt} \end{array}$$

Only one parse tree for
if E_1 **then if** E_2 **then** S_1 **else** S_2
Associates each **else** with closest previous unmatched **then**

2.3 Syntax-Directed Translation

Using the syntactic structure of the language to generate output corresponding to some input

Two techniques:

- Syntax-directed definition
- Translation scheme

Example: translation of infix notation to postfix notation

infix	postfix
$(9 - 5) + 2$	$95 - 2+$
$9 - (5 + 2)$	$952 + -$

What is $952 + -3*$?

Syntax-Directed Translation

Using the syntactic structure of the language to generate output corresponding to some input

Two variants:

- Syntax-directed definition
- Translation scheme

Example: translation of infix notation to postfix notation

Simple infix expressions generated by

$$\begin{array}{rcl} \mathit{expr} & \rightarrow & \mathit{expr}_1 + \mathit{term} \mid \mathit{expr}_1 - \mathit{term} \mid \mathit{term} \\ \mathit{term} & \rightarrow & 0 \mid 1 \mid \ldots \mid 9 \end{array}$$

Syntax-Directed Definition (Example)

Production	Semantic rule
$expr \rightarrow expr_1 + term$	$expr.t = expr_1.t \mid\mid term.t \mid\mid `+'$
$expr \rightarrow expr_1 - term$	$expr.t = expr_1.t \mid\mid term.t \mid\mid `-'$
$expr \rightarrow term$	$expr.t = term.t$
$term \rightarrow 0$	$term.t = `0'$
$term \rightarrow 1$	$term.t = `1'$
$\ldots$	$\ldots$
$term \rightarrow 9$	$term.t = `9'$

Result: annotated parse tree

Example: $9 - 5 + 2 \ldots$

Syntax-Directed Definition

- Uses a context-free grammar to specify the syntactic structure of the language

- Associates a set of *attributes* with (non)terminals

- Associates with each production a set of *semantic rules* for computing values for the attributes

In example, attributes contain the translated form of the input after the computations are completed
(postfix notation corresponding to subtree)

Synthesized and Inherited Attributes

An attribute is said to be . . .

- synthesized if its value at a parse tree node N is determined from attribute values at the children of N (and at N itself)

- inherited if its value at a parse tree node N is determined from attribute values at the parent of N (and at N itself and its siblings)

We (mainly) consider synthesized attributes

2.3.4 Tree Traversals

- A syntax-directed definition does not (. . .) impose an evaluation order of the attributes on a parse tree
- Different orders might be suitable
- *Tree traversal*: a specific order to visit the nodes of a tree (always starting from the root node)
- Depth-first traversal
  - Start from root
  - Recursively visit children (in any order)
  - Hence, visit nodes far away from the root as quickly as it can (DF)

A Possible DF Traversal

Postorder traversal

```
procedure visit (node N)
{
  for (each child C of N, from left to right)
  { visit (C);
  }
  evaluate semantic rules at node N;
}
```

Can be used to determine synthesized attributes / annotated parse tree

2.3.5 Translation Scheme

A translation scheme is a context-free grammar
with semantic actions embedded in the bodies of the productions
(which may also involve attributes of the grammar symbols)

Example

$$\begin{array}{lcl} \mathit{expr} & \rightarrow & \mathit{expr}_1 + \mathit{term} \mid \mathit{expr}_1 - \mathit{term} \mid \mathit{term} \\ \mathit{term} & \rightarrow & 0 \mid 1 \mid \ldots \mid 9 \end{array}$$

Translation Scheme (Example)

$$\begin{array}{rcl}
\mathit{expr} & \rightarrow & \mathit{expr}_1 + \mathit{term}\ \{\text{print('+')}\} \\
\mathit{expr} & \rightarrow & \mathit{expr}_1 - \mathit{term}\ \{\text{print('$-$')}\} \\
\mathit{expr} & \rightarrow & \mathit{term} \\
\mathit{term} & \rightarrow & 0\ \{\text{print('0')}\} \\
\mathit{term} & \rightarrow & 1\ \{\text{print('1')}\} \\
\ldots & & \ldots \\
\mathit{term} & \rightarrow & 9\ \{\text{print('9')}\}
\end{array}$$

Example: parse tree for $9-5+2\ldots$

Implementation requires postorder traversal (LRW)

Translations Scheme

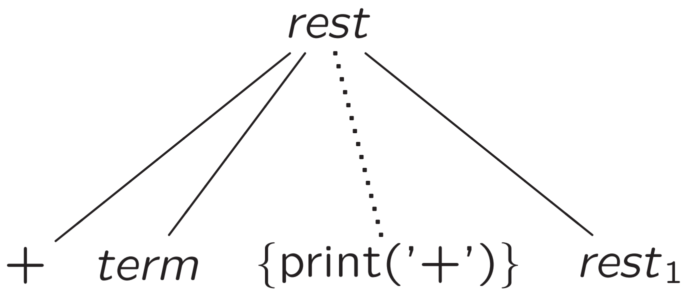
Different grammar for same expressions:

$$\mathit{rest} \;\rightarrow\; +\mathit{term}\ \mathit{rest}_1$$

With semantic action:

$$\mathit{rest} \;\rightarrow\; +\mathit{term}\ \{\text{print('+')}\}\ \mathit{rest}_1$$

Corresponding effect on parse tree:



Translations Scheme

Different grammar for same expressions:

$$\begin{array}{rcl} \textit{expr} & \rightarrow & \textit{term rest} \\ \textit{rest} & \rightarrow & +\textit{term rest}_1 \\ \textit{rest} & \rightarrow & -\textit{term rest}_1 \\ \textit{rest} & \rightarrow & \epsilon \\ \textit{term} & \rightarrow & 0 \\ \textit{term} & \rightarrow & \ldots \end{array}$$

With semantic action:

$$\begin{array}{rcl} \textit{rest} & \rightarrow & +\textit{term}\ \{\text{print('+')}\}\ \textit{rest}_1 \\ \textit{rest} & \rightarrow & -\textit{term}\ \{\text{print('}-\text{')}\}\ \textit{rest}_1 \\ \textit{term} & \rightarrow & 0\ \{\text{print('0')}\} \\ \textit{term} & \rightarrow & \ldots \end{array}$$

Complete parse tree $9 - 5 + 2 \ldots$

2.4 Parsing

- Process of determining if a string of tokens can be generated by a grammar

- For any context-free grammar, there is a parser that takes at most $\mathcal{O}(n^3)$ time to parse a string of n tokens

- Linear algorithms sufficient for parsing programming languages

- Two methods of parsing:
  - Top-down constructs parse tree from root to leaves
  - Bottom-up constructs parse tree from leaves to root

Cf. top-down PDA and bottom-up PDA in FI2

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Overview

Chapters for reading: 1.1, 1.2, 2.1-2.3, 2.5