



# Compiler Construction

Lecture 1: Introduction

Winter Semester 2018/19

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<https://moves.rwth-aachen.de/teaching/ws-1819/cc/>

# Preliminaries

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## People

- Lectures:
  - **Thomas Noll** ([noll@cs.rwth-aachen.de](mailto:noll@cs.rwth-aachen.de))
- Exercise classes:
  - **Philipp Berger** ([berger@cs.rwth-aachen.de](mailto:berger@cs.rwth-aachen.de))
  - **Matthias Volk** ([matthias.volk@cs.rwth-aachen.de](mailto:matthias.volk@cs.rwth-aachen.de))
- Student assistant:
  - **Justus Fesefeldt**

## Target Audience

- **BSc Informatik:**
  - Wahlpflicht Theoretische Informatik
- **MSc Informatik:**
  - Wahlpflicht Theoretische Informatik
- **MSc Software Systems Engineering:**
  - Theoretical Foundations of SSE
- ...

## Expectations

- What **you** can expect:
  - how to implement (imperative) programming languages
  - application of theoretical concepts (scanning, parsing, static analysis, ...)
  - compiler = example of a complex software architecture
  - gaining experience with tool support
- What **we** expect: basic knowledge in
  - (imperative) programming languages
  - algorithms and data structures (queues, stacks, trees, ...)
  - formal languages and automata theory (regular and context-free languages, finite and pushdown automata, ...)

## Organisation

- **Schedule:**
  - Lecture Mon 12:30–14:00 AH 6 (starting 8 Oct)
  - Lecture Thu 12:30–14:00 AH 5 (starting 11 Oct)
  - Exercise class Mon 15:15–16:45 AH 5 (starting 15 Oct)
  - Two special lectures in mid-December (itestra)
  - see overview at <https://moves.rwth-aachen.de/teaching/ws-1819/cc/>
- **Exercises:**
  - **1st assignment sheet** next week, presented 22 Oct
  - Work on assignments in **groups of threefour** people
  - Recap of foundations (finite automata, ...) on 15 Oct
- **Exam:**
  - **Written exams** (2 h, 6 Credits) 21.02.2019 and 25.03.2019
  - **Registration** between 3 Dec and 10 Jan
  - **Admission** requires at least 50% of the points in the exercises
- Written material in **English** (including exam), lecture and exercise classes in **German**, rest up to you

# What Is a Compiler?

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## What Is It All About?

<https://en.wikipedia.org/wiki/Compiler>

“A compiler is computer software that **transforms** computer code written in one programming language (the **source language**) into another programming language (the **target language**)... The name compiler is primarily used for programs that translate source code from a **high-level programming language** to a **lower level language** (e.g., assembly language, object code, or machine code) to create an **executable program**.”

## Compiler vs. interpreter

**Compiler:** **translates** an executable program in one language into an executable program in another language (possibly applying “improvements”)

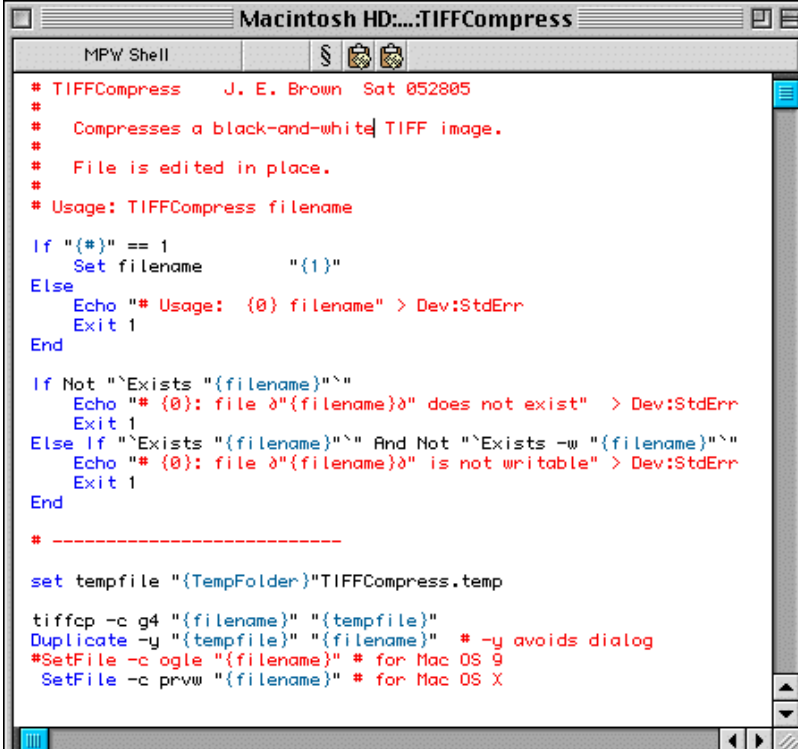
**Interpreter:** directly **executes** an executable program, producing the corresponding results

# What Is a Compiler?

## Usage of Compiler Technology I

### Programming language interpreters

- Ad-hoc implementation of small programs in **scripting languages** (JavaScript, Perl, Ruby, bash, ...)
- Programs usually **interpreted**, i.e., executed stepwise
- Moreover: many non-scripting languages also involve interpreters (e.g., JVM as byte code interpreter)



```
MPW Shell
# TIFFCompress  J. E. Brown  Sat 052805
#
# Compresses a black-and-white TIFF image.
# File is edited in place.
# Usage: TIFFCompress filename

If {"#" == 1
  Set filename      "{1}"
Else
  Echo "# Usage: {0} filename" > Dev:StdErr
  Exit 1
End

If Not "`Exists "{filename}"`"
  Echo "# {0}: file `"{filename}`" does not exist" > Dev:StdErr
  Exit 1
Else If "`Exists "{filename}"`" And Not "`Exists -w "{filename}"`"
  Echo "# {0}: file `"{filename}`" is not writable" > Dev:StdErr
  Exit 1
End

# -----

set tempfile "{TempFolder}"TIFFCompress.temp

tiffcp -c g4 "{filename}" "{tempfile}"
Duplicate -y "{tempfile}" "{filename}" # -y avoids dialog
#SetFile -c ogle "{filename}" # for Mac OS 9
SetFile -c prvw "{filename}" # for Mac OS X
```

# What Is a Compiler?

## Usage of Compiler Technology II

### Web browsers

- Receive **HTML (XML)** pages from web server
- Analyse (**parse**) data and **translate** it to graphical representation

```
1 <!DOCTYPE html PUBLIC "-//W3C//DTD HTML
2 <html>
3   <head>
4     <title>Example</title>
5     <link href="screen.css" rel="sty
6   </head>
7   <body>
8     <h1>
9       <a href="/">Header</a>
10    </h1>
11    <ul id="nav">
12      <li>
13        <a href="one/">One</a>
14      </li>
15      <li>
16        <a href="two/">Two</a>
17      </li>
```



# What Is a Compiler?

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## Usage of Compiler Technology III

### Text processors

- $\text{\LaTeX}$  = “programming language” for texts of various kinds
- Translated to DVI, PDF, ...

```
\documentclass[12pt]{article}
%options include 12pt or 11pt or 10pt
%classes include article, report, book, letter, thesis
\title{This is the title}
\author{Author One \ \ Author Two}
\date{\today}
\begin{document}
\maketitle
This is the content of this document.
This is the 2nd paragraph.
Here is an inline formula:

$$V = \frac{4}{3} \pi r^3$$

And appearing immediately below
is a displayed formula:

$$V = \frac{4}{3} \pi r^3$$

\end{document}
```

## Expected Properties of a Compiler I

### Correctness of translation

#### Goals:

**syntactic correctness:** **conformance** to source and target language specifications

- accept all (and only) syntactically valid input programs
- produce correct target code

**semantic correctness:** **“equivalence”** of source and target code

- behaviour of target code “corresponds to” (expected) behaviour of source code

#### Techniques:

- compiler validation and verification
- proof-carrying code, ...
- cf. course on *Semantics and Verification of Software* (WS 2017/18, SS 2019)

## Expected Properties of a Compiler II

### Efficiency of generated code

**Goal:** target code as **fast** and/or **memory efficient** as possible

**Techniques:**

- program analysis and optimisation
- cf. course on *Static Program Analysis* (SS 2018)

### Efficiency of compiler

**Goal:** translation process as **fast** and/or **memory efficient** as possible (for input programs of arbitrary size)

**Techniques:**

- fast (linear-time) algorithms
- sophisticated data structures

**Remark:** **mutual tradeoffs!**

# Aspects of a Compiler

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## Aspects of a Programming Language

### Syntax: “How does a program look like?”

- hierarchical composition of programs from structural components (keywords, identifiers, expressions, statements, ...)

### Semantics: “What does this program mean?”

- “Static semantics”: properties which are not (easily) definable in syntax (declaredness of identifiers, type correctness, ...)
- “Operational semantics”: execution evokes state transformations of an (abstract) machine

### Pragmatics

- length and understandability of programs
- learnability of programming language
- appropriateness for specific applications
- ...

## Motivation for Rigorous Formal Treatment

### Example 1.1

1. From NASA's Mercury Project: FORTRAN `DO` loop

– `DO 5 K = 1,3`: DO loop with index variable `K`

– `DO 5 K = 1.3`: assignment to (`real`) variable `D05K`

(cf. Dirk W. Hoffmann: *Software-Qualität*, 2nd ed., Springer 2013)

2. How often is the following loop traversed?

```
for i := 2 to 1 do ...
```

**FORTRAN IV:** once

**Pascal:** never

3. What if value of `p` is `nil` in the following program?

```
while p <> nil and p^.key < val do ...
```

**Pascal:** strict Boolean operations ⚡

**Modula:** non-strict Boolean operations ✓

# Aspects of a Compiler

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## Historical Development

Code generation: since 1940s

- ad-hoc techniques
- concentration on back-end
- first FORTRAN compiler in 1960

Formal syntax: since 1960s

- LL/LR parsing
- shift towards front-end
- semantics defined by compiler/interpreter

Formal semantics: since 1970s

- operational
- denotational
- axiomatic
- cf. course on *Semantics and Verification of Software*

Automatic compiler generation: since 1980s

- [f]lex, yacc/bison, ANTLR, ...
- cf. <https://www.thefreecountry.com/programming/compilerconstruction.shtml>

# The High-Level View

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## Compiler Phases

### Lexical analysis (Scanner):

- recognition of symbols, delimiters, and comments
- by regular expressions and finite automata

### Syntax analysis (Parser):

- determination of hierarchical program structure
- by context-free grammars and pushdown automata

### Semantic analysis:

- checking context dependencies, data types, ...
- by attribute grammars

### Generation of intermediate code:

- translation into (target-independent) intermediate code
- by tree translations

**Code optimisation:** to improve runtime and/or memory behavior

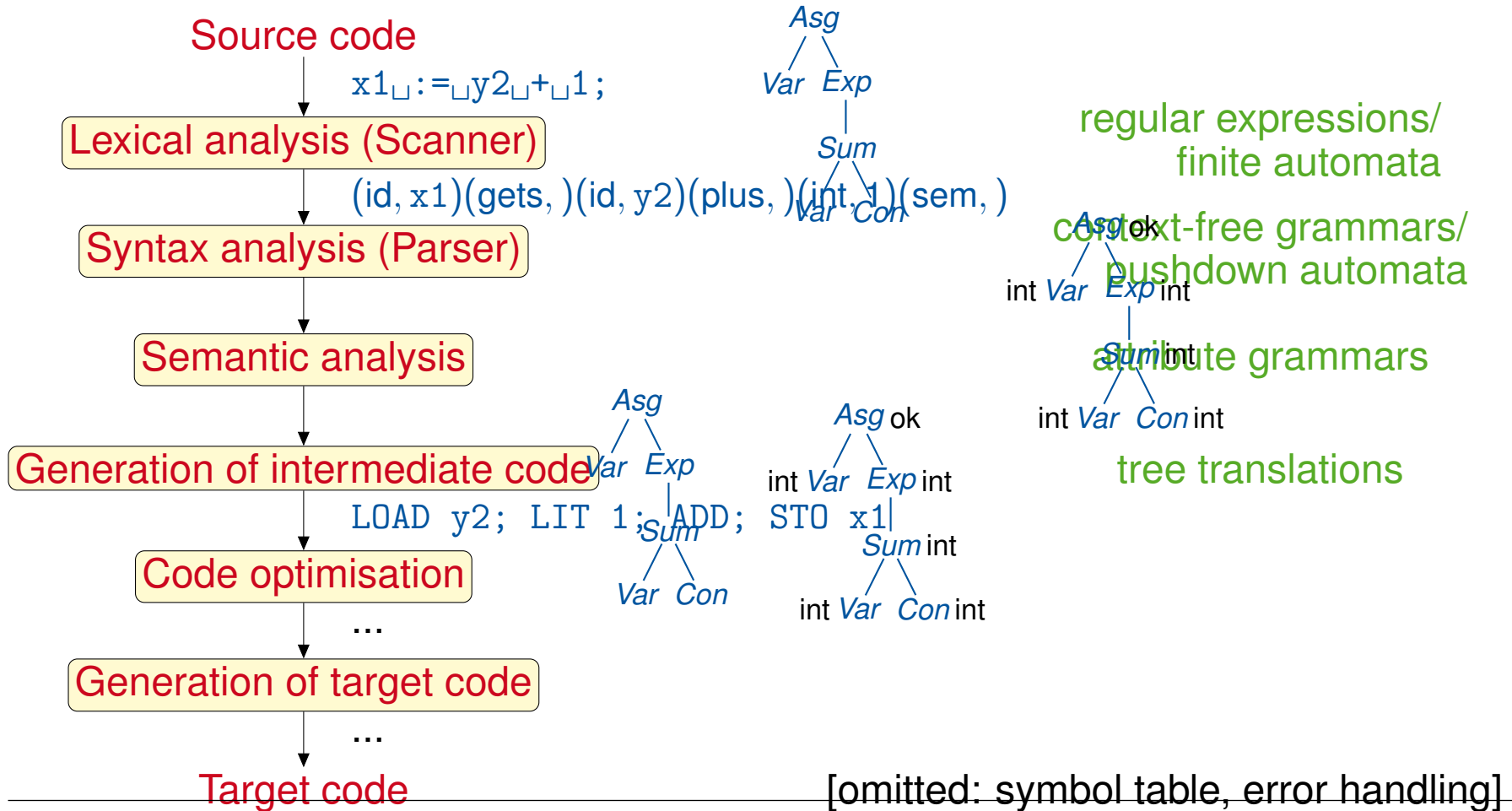
**Generation of target code:** tailored to target system

**Additionally:** optimisation of target code, symbol table, error handling

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# The High-Level View

## Conceptual Structure of a Compiler





# The High-Level View

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## Classification of Compiler Phases

### Analysis vs. synthesis

**Analysis:** lexical/syntax/semantic analysis

(determination of syntactic structure, error handling)

**Synthesis:** generation of (intermediate/target) code + optimisation

### Front-end vs. back-end

**Front-end:** machine-independent parts

(analysis + intermediate code + machine-independent optimisations)

**Back-end:** machine-dependent parts (generation + optimisation of target code)

- instruction selection
- register allocation
- instruction scheduling

## Role of the Runtime System

- Memory management services
  - allocation (on heap/stack)
  - deallocation
  - garbage collection
- Run-time type checking (for non-“strongly typed” languages)
- Error processing, exception handling
- Interface to the operating system (input and output, ...)
- Support for parallelism (communication and synchronisation)

## Literature (CS Library: “Handapparat *Softwaremodellierung und Verifikation*”)

### General

- A.V. Aho, M.S. Lam, R. Sethi, J.D. Ullman: *Compilers – Principles, Techniques, and Tools; 2nd ed.*, Addison-Wesley, 2007
- A.W. Appel, J. Palsberg: *Modern Compiler Implementation in Java*, Cambridge University Press, 2002
- D. Grune, H.E. Bal, C.J.H. Jacobs, K.G. Langendoen: *Modern Compiler Design*, Wiley & Sons, 2000
- R. Wilhelm, D. Maurer: *Übersetzerbau, 2. Auflage*, Springer, 1997

### Specific

- O. Mayer: *Syntaxanalyse*, BI-Wissenschafts-Verlag, 1978
- D. Brown, R. Levine T. Mason: *lex & yacc*, O’Reilly, 1995
- T. Parr: *The Definite ANTLR Reference*, Pragmatic Bookshelf, 2007