TDDE66/TDDD55 Lecture 1: Compiler Construction Introduction

Adrian Pop and Martin Sjölund

Department of Computer and Information Science
Linköping University

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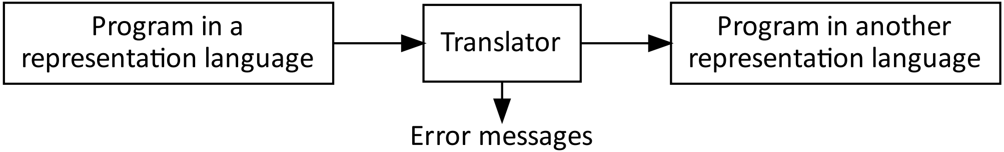
Introduction, Translators

- Compiler



- High-level language → machine language or assembly language (Pascal, Ada, Fortran, Java, ...)
- Three phases of execution:

"Compile-time"

1. Source program → object program (compiling)
2. Linking, loading → absolute program

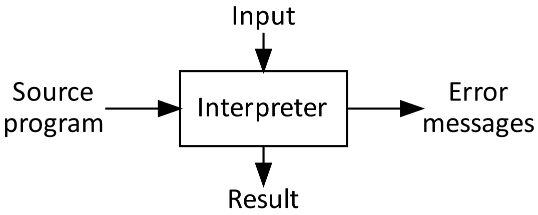
"Run-time"

3. Input → output

Interpreters

High-level language $\rightarrow$ intermediate code – which is *interpreted* directly, not translated, such as:

- BASIC, LISP, APL
- command languages such as UNIX-shell
- query languages for databases
- Early versions of JavaScript interpreters



Assembler

Symbolic machine code $\rightarrow$ machine code, for example:

MOVE R1,SUM $\quad\rightarrow\quad$ 01..101

Simulator, Emulator

Machine code *is interpreted* $\rightarrow$ machine code

Examples:

- Simulate a processor on an existing processor
- Running qemu on an amd64 laptop to run ARM Linux to test things
- Running old games on modern hardware

Generally, an emulator will try to mimic the behavior of the foreign architecture as best it can. A simulator will try to model the entire state of the foreign processor.

Preprocessor/Macro

Extended (“sugared”) high-level language → high-level language

Listing 1: ”IF-THEN-ELSE in FORTRAN”

```
IF A < B THEN
  Z=A
ELSE
  Z=B
```

Listing 2: ”FORTRAN after preprocessing”

```
    IF (A.LT.B) THEN GOTO 99
    Z=B
    GOTO 100
99  Z=A
100 CONTINUE
```

Listing 3: ”File inclusion in C”

```
#include <unistd.h>
```

Natural Language – Translators

For example Chinese $\rightarrow$ English

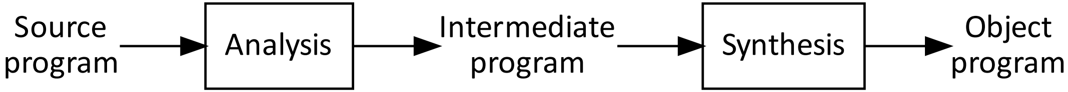
Very difficult problem, especially to include context:

- Example 1: *Visiting relatives* can be hard work
  - To *go and visit* relatives ...
  - Relatives who *are visiting* ...
- Example 2: I saw a man with *a telescope*

Why High-Level Languages?

- Understandability (readability)
- Naturalness (languages for different applications, DSL)
- Portability (machine-independent)
- Efficient to use (development time) due to
  - separation of data and instructions
  - typing
  - data structures
  - blocks
  - program-flow primitives (if, switch, for, while, do-until, exceptions, goto)
  - subroutines

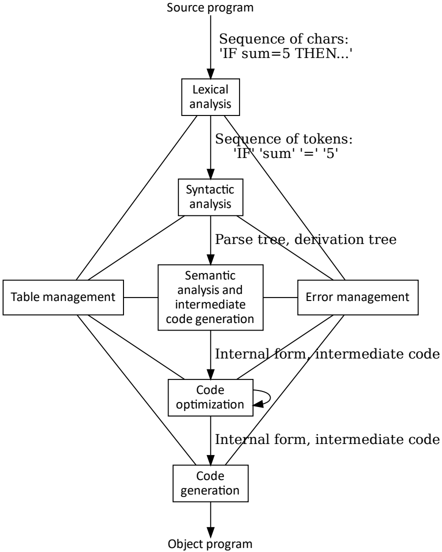
The Structure of the Compiler



Logical organization

- Analysis ("front-end"):
  Pull apart the text string (the program) to internal structures, reveal the structure and meaning of the source program.
- Synthesis ("back-end"):
  Construct an object program using information from the analysis.

The Phases of the Compiler



Compiler Passes and Phases

- Pass:
  - Physical organization (phase to phase) dependent on language and compromises.
  - Available memory space, efficiency (time taken), forward references, portability- and modularity- requirements determine the number of passes.
- The number of passes: (one-pass, multi-pass)
  - The number of times the program is written into a file (or is read from a file).
  - Several phases can be gathered together in one pass.

Lexical Analysis (Scanner)

- Input:
  - Sequence of characters
- Output:
  - Tokens (basic symbols, groups of successive characters which belong together logically).

1. In the source text isolate and classify the basic elements that form the language:

Tokens	*Example*
Identifiers	Sum, A, id2
Constants	556, 1.5e-5
Strings	"Provide a number"
Keywords, reserved words	while, if
Operators	$* \, / \, + \, -$
Others	. :

2. Construct tables (symbol table, constant table, string table etc.).

Scanner Lookahead for Tricky Tokens

Listing 4: FORTRAN

```
! A loop
  DO 10 I=1,15
! An assignment DO10I = 1.15
  DO 10 I=1.15
! Blanks have no meaning in FORTRAN.
```

Listing 5: Pascal

```
VAR i: 15..25;
(* 15 is an integer *)
(* 15. is a real *)
(* 15.. an integer and .. *)
```

Scanner Return Values

Regular expressions are used to describe tokens, which the scanner returns values in the form: <type, value>

Listing 6: Example: IF sum < 15 THEN z :

```
< 5, 0 >    5 = IF, 0 = lacks value
< 7, 14 >   7 = code for identifier, 14 = entry to
   symbol table
< 9, 1 >    9 = relational operator, 1 = '<'
< 1, 15>    1 = code for constant, 15 = value
< 2, 0 >    2 = THEN, 0 = lacks value
< 7, 9 >    7 = code for identifier, 9 = entry to
   symbol table
< 3, 0 >    3 = ':=', 0 = lacks value
< 1,153 >   1 = code for constant, 153 = value
```

Table: Symbol Table

Index	**Symbol**	**Data**
⋮		
9	z	...
⋮		
14	sum	...

Syntax Analysis (parsing) 1 – Checking

- Input: Sequence of tokens + symbol table
- Output: Parse tree, error messages
- Function: (1) Determine whether the input sequence forms a structure which is legal according to the definition of the language.

Listing 7: OK

```
'IF' 'X' '=' '1' 'THEN' 'X' ':=' '1'
```

Listing 8: Not OK

```
'IFF' 'X' '=' '1' 'THEN' 'X' ':=' '1'
```

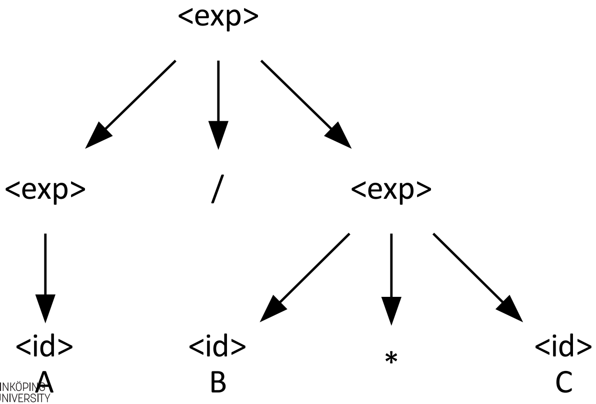
which produces the sequence of tokens:

```
< 7, 23 >
< 7, 16 > {Two identifiers in a row is wrong}
< 9, 0 >
```

Syntax Analysis (parsing) 2 – Build Trees

Function: (2) Group tokens into syntactic units and construct parse trees which exhibit the structure. Stop on first error or continue.

Figure: Example: A / B * C



This represents A / (B * C) i.e. right-associative (is this desirable?)
The alternative would be: (A / B) * C – not the same!
The syntax of a language is described using a context-free grammar.

Semantic Analysis and Intermediate Code Generation 1 – More Checking

- Input: Parse tree + symbol table
- Output: Intermediate code + symbol table temp.variables, information on their type ...
- Function:
  Semantic analysis checks items which a grammar can not describe, e.g.
  - type compatibility a := i * 1.5
  - correct number and type of parameters in calls to procedures as specified in the procedure declaration.

Semantic Analysis and Intermediate Code Generation 2 - Generate Intermediate Code

Example: $A + B * C$

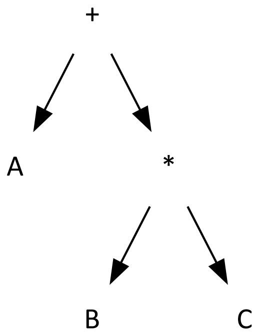
Listing 9: Reverse Polish notation

```
A B C * +
```

Listing 10: Three-address code

```
T1 := B * C
T2 := A + T1
```

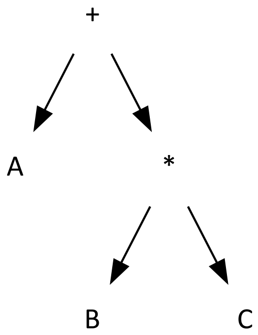
Figure: Abstract syntax tree



Semantic Analysis and Intermediate Code Generation 3 - Intermediate Code

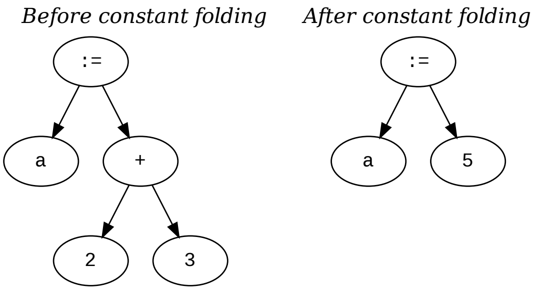
- The intermediate form is used because it is:
  - Simpler than the high-level language (fewer and simpler operations).
  - Not profiled for a given machine (portability).
  - Suitable for optimization.
- Syntax-directed translation schemes are used to attach semantic routines (rules) to syntactic constructions.

Figure: Abstract syntax tree



Code Optimization (CO) - more appropriately: "Code Improvement"

- Input: Internal form
- Output: Internal form (hopefully improved)
- Machine-independent code optimization:
  - In some way make the machine code faster or more compact by transforming the internal form.



Code Generation

- Input: Internal form
- Output: Machine code/assembly code
- Function:
  1. Register allocation and machine code generation (or assembly code).
  2. Instruction scheduling (specially important for RISC).
  3. Machine-dependent code optimization (so-called "peephole optimization").

Listing 11: Z := A + B * C is translated to assembly code

```
MOVE  R1, B
IMUL  R1, C
ADD   R1, A
MOVEM R1, Z
```

Compiler evolution in the last 20 years - I

- Language diversity - more flexible compilers
- Better optimization techniques - loop optimizations, automatic vectorization and JIT
- Parallel and Multicore Support - compiler adaptation was needed - automatic parallelization and parallel languages
- Just-in-Time Compilation: JIT compilers for dynamic languages
- Better Intermediate Representation - to enable more optimization and better code generation
- Better Compiler Frameworks - LLVM, GCC, rust, C#, Go, TS, WebAssembly

Compiler evolution in the last 20 years - II

- Language-Independent Tools - for various compiler phases parsing, type checking, code generation - greater flexibility and IDE improvements (LSP, etc)
- Better Error Reporting - much easier to fix errors
- Improved Security - stack checks (canaries), address sanitizer, control-flow integrity checks. Different computation paradigms for safety (rust).
- Compiler Verification via formal methods - advancements, can be used on non-toy examples to guarantee compiler correctness for safety critical systems.
- Support new architectures - mobile, IoT, edge, cloud, GPUs, TPUs, FPGAs, etc.
- ML & AI for compiler construction to automate CO and CG
- AI to generate a compiler for your DSL automatically (might work)

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