Chapter 1: Overview of Compilation

A Presentation by Gregory Breard

Introduction

- Today we will be discussing compilers. This will be a rather high-level introduction to compiler design, and most of the material covered should be familiar to you.

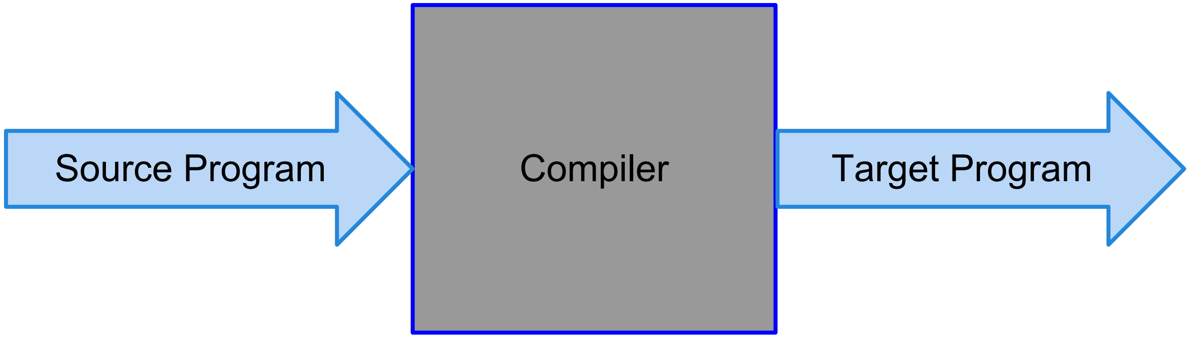
- **Compiler** - a computer program that translates other computer programs to prepare them for execution

Conceptual Roadmap

- Compilers translate software written in one language into another language.
- To perform this translation, the compiler must:
  - Understand the form of the language (or **syntax**)
  - Understand the meaning of the language (or **semantics**)
  - And have a scheme for mapping content from the source language to the target language
- Compilers typically have a **front end** for dealing with the source language, and a **back end** for dealing with the target language.

Overview

- In general, compilers translate programming languages into machine instructions for a specific processor (or **target machine**)
- Viewed as a *black box*:



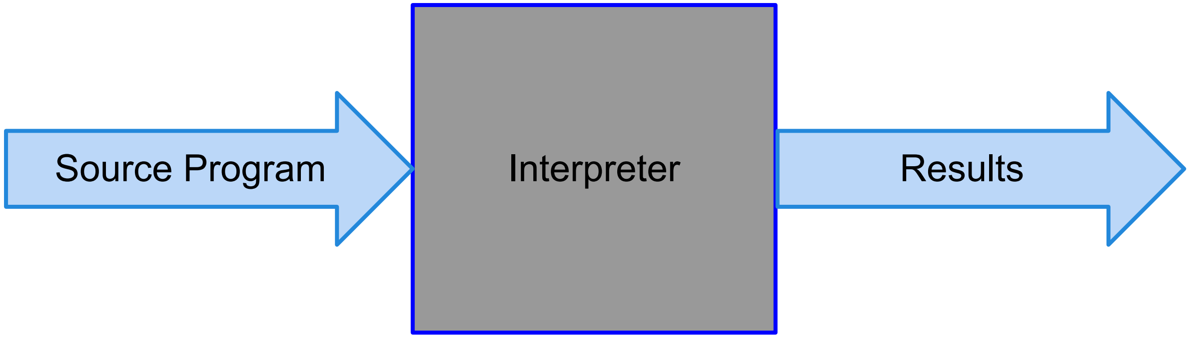
- Typical source languages are: C++, Java, etc.
- The target language is usually the instruction set of the target machine

Overview (continued)

- **Instruction set** - the set of operations supported by a processor; the overall design of an instruction set is often called an *instruction set architecture* (or ISA).
- Some compilers target programming languages instead of an instruction set, these are referred to as *source-to-source translators*
- There are many other systems that qualify as compilers (i.e. typesetting programs)

Overview (continued)

- A program that reads source code and produces results (instead of translating to a target language) is called an **interpreter**.



- Some languages' translation schemes include both compilation and interpretation, one example being Java.

Overview (continued)

- Java is compiled into *bytecode,* which is then executed by a bytecode interpreter, the Java Virtual Machine (JVM)
- **Virtual machine** - A virtual machine is a simulator for some processor. It is an interpreter for that machine's instruction set.

- Compilers and interpreters are similar and perform many of the same tasks. However, the outputs of these programs are significantly different.

The Fundamental Principles of Compilation

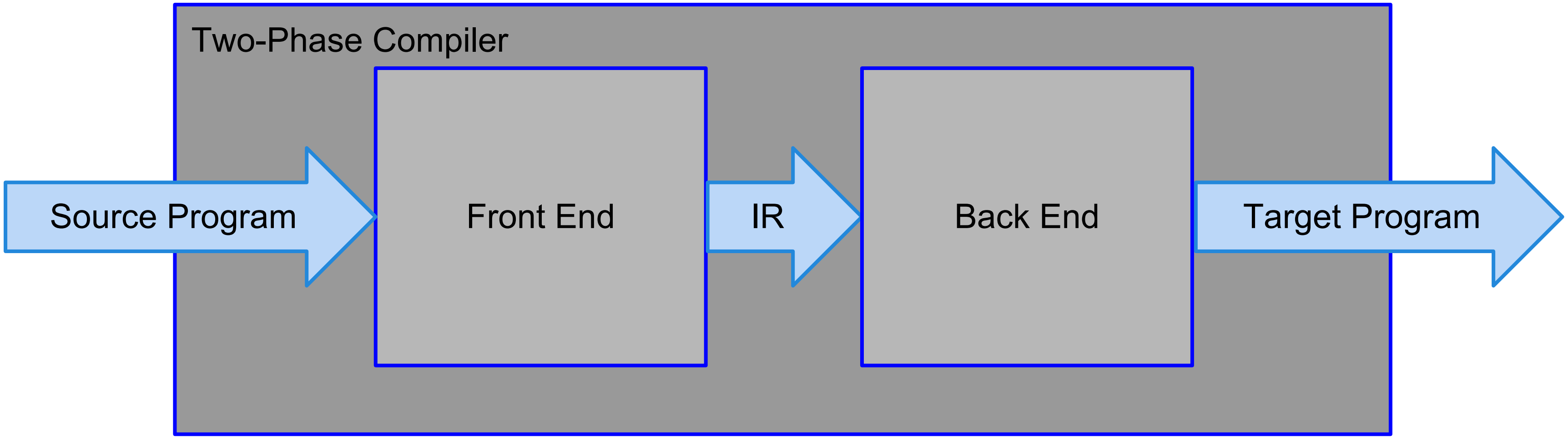
- There are two fundamental principles of compilation that are essential to compiler design:

1. *The compiler must preserve the meaning of the program being compiled.*

2. *The compiler must improve the input program in some discernible way.*

Compiler Structure

- A compiler must both understand the source program and map its functionality to the target machine
- These two distinct tasks are separated into the *front end* and *back end* of the compiler



Compiler Structure (continued)

- The front end focuses on understanding the source language program
- The back end focuses on mapping programs to the target language
- Between these tasks, the compiler uses an **intermediate representation** (IR) to store information about the program
- **IR** - A compiler uses some set of data structures to represent the code that it processes. That form is called an *intermediate representation*.

Compiler Structure (continued)

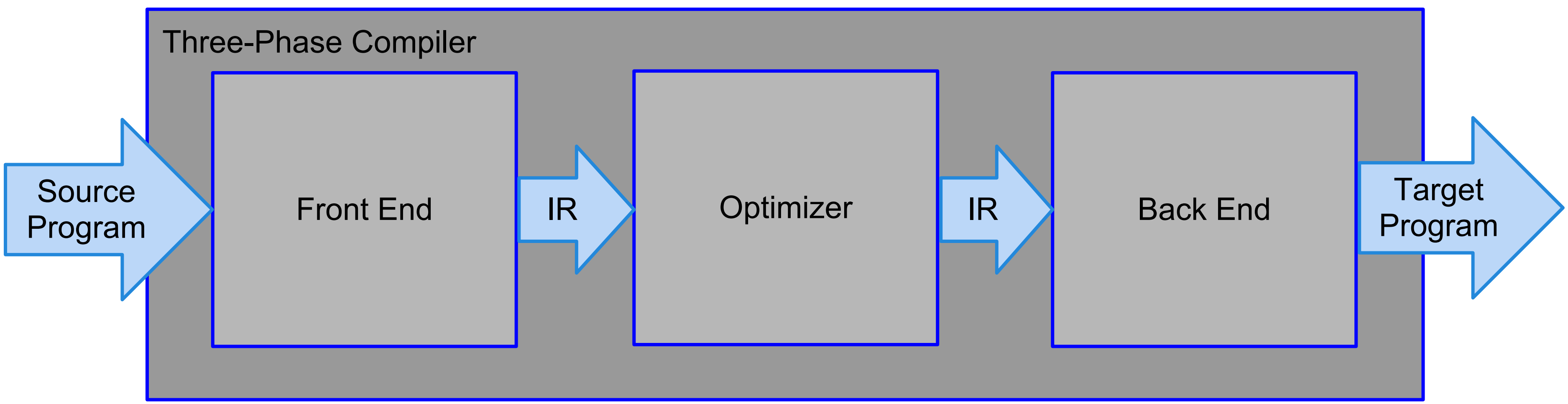
- The IR is a definitive representation of the code it is translating.
- Compilers may even use several different IRs depending on the task it is performing.
- The front end ensures the source code is well formed, and maps it to the IR.
- The back end therefore only processes the IR, and can assume the IR contains no syntactic or semantic errors.

Compiler Structure (continued)

- This *two-phase* approach to compiling also simplifies the process of retargeting.
- **Retargeting** - the task of changing the compiler to generate code for a new processor is often called *retargeting* the compiler.
- The compiler can be made to read a different source program by changing out the front end. Similarly, the compiler can be made to translate to a different target program by changing out the back end.

Compiler Structure (continued)

- A compiler can also have a third phase added between the front end and back end, an *optimizer*.
- **Optimizer** - analyzes and transforms the IR to improve it.



Compiler Structure (continued)

- The optimizer is an IR-to-IR transformer
- It can make one or more passes over the IR, analyzing and rewriting it.
- The optimizer may have a variety of objectives, i.e. a faster target program or a smaller target program
- It should be noted that although the term *optimization* is used, the problems of optimization are so complex and interrelated that they cannot, in practice, be solved optimally.

Overview of Translation

- In translating from a programming language to machine executable code, a compiler runs through many steps.
- Following, we will discuss the steps taken by:
  - The Front End
  - The Optimizer
  - The Back End

The Front End

- Before translating the code, the compiler must understand the syntax and semantics of the source program.
- If the syntax and semantics are valid, the front end produces an intermediate representation for the source program
- If the syntax or semantics are invalid, a diagnostic error message is returned to the user and compilation is halted.

The Front End: Checking Syntax

- To check the syntax of a program, the compiler must compare the program's structure to a definition of the language.
- The source language is defined by a finite set of rules, called a **grammar**.
- Programming language grammars refer to words by their parts of speech, or syntactic categories.

The Front End: Checking Syntax (continued)

- For example, an English sentence may have the definition:

  Sentence → *Subject* `verb` *Object* `endmark`
- Here, `verb` and `endmark` are parts of speech and *Subject* and *Object* are syntactic variables.
- *Sentence* represents any string with the form described by the rule.
- The → symbol is read "derives" and means the instance on the right can be abstracted to the syntactic variable on the left.

The Front End:
Checking Syntax (continued)

- Two separate passes in the front end (called the *scanner* and the *parser*) determine if the input program is valid.
- **Scanner** - the compiler converts a string of characters into a stream of classified words.
- **i.e.** "Compilers are engineered objects." would be converted to the (part of speech, spelling) pairs:

  (`noun`, "Compilers"), (`verb`, "are"), (`adjective`, engineered"),(`noun`, "objects"), (`endmark`, ".")

The Front End: Checking Syntax (continued)

- **Example grammar:**

Sentence → *Subject* `verb` *Object* `endmark`

Subject → `noun`

Subject → *Modifier* `noun`

Object → `noun`

Object → *Modifier* `noun`

Modifier → `adjective`

The Front End: Checking Syntax (continued)

- **Parser** - performs a series of automatic derivations in order to determine if the input stream is a sentence in the language definition.
- Derivation for our example:

Sentence

Subject `verb` *Object* `endmark`

`noun verb` *Object* `endmark`

`noun verb` *Modifier* `noun endmark`

`noun verb adjective noun endmark`

The Front End: Checking Syntax (continued)

- However, a grammatically correct sentence may be meaningless **i.e.** "Rocks are green vegetables."
- Semantic analysis is used to determine if a sentence's "meaning" is valid
- One example of semantic analysis is checking for type consistency **i.e.** to make sure an `int` is not assigned a `string` value
- **Type Checking** - the compiler pass that checks for type-consistent uses of names in the input progam.

The Front End: Intermediate Representation

- The front end is also responsible for generating the IR
- Compilers use a variety of different types of IRs, depending on the specific needs of the compiler.
- However, for every source-language construct the compiler needs a strategy for how it will implement the construct in the IR.

The Optimizer

- The optimizer analyzes the IR to discover facts about how the code will behave at runtime.
- It then uses this information to rewrite the code so that it produces the same answer in a more efficient way.
- Efficiency can have many meanings in this context, **i.e.** reduced running time, reduced compiled code size, reduced processor energy consumption, etc.

The Optimizer: Analysis

- The first step of optimization is to analyze the code to determine where the compiler can safely and profitably apply transformations.
- Compilers use several kinds of analysis.
- **Data-flow analysis** - a form of compile time reasoning about the runtime flow of values.
- **Dependence analysis** - uses number-theoretic tests to reason about the values that can be assumed by subscript expressions.

The Optimizer: Transformation

- After analyzing the code, the compiler must use the results to rewrite the code in a more efficient form.
- A multitude of transformations have been invented do just that.
- One example is to move loop-invariant computations outside of loops to improve running time of the program.
- Transformations vary in their effect, the scope over which they operate, and the analysis required to support them.

The Back End

- The back end reads the IR and generates code for the target machine
- It selects target machine operations to perform the operations represented in the IR and chooses an order in which these operations will execute efficiently.
- It also decides which values will reside in registers and which will reside in memory, and generates the code that will enforce these decisions.

The Back End: Instruction Selection

- The first step in code generation is *instruction selection*, in which each IR operation is rewritten as one or more target machine operations.
- **Example:** `a ← a * 2 * b * c`

  IR for the expression:

  $t_0 \leftarrow a * 2$

  $t_1 \leftarrow t_0 * b$

  $t_2 \leftarrow t_1 * c$

  $a \leftarrow t_2$

The Back End: Instruction Selection (continued)

- Rewritten for the ILOC virtual machine:

```
loadAI  r_arp, @a ⇒ r_a   // load 'a'
loadI   2         ⇒ r_2   // constant 2 into r_2
loadAI  r_arp, @b ⇒ r_b   // load 'b'
loadAI  r_arp, @c ⇒ r_c   // load 'c'
mult    r_a, r_2  ⇒ r_a   // r_a = a * 2
mult    r_a, r_b  ⇒ r_a   // r_a = (a * 2) * b
mult    r_a, r_c  ⇒ r_a   // r_a = (a * 2 * b) * c
storeAI r_a       ⇒ r_arp,@a // write r_a back to
                             // 'a'
```

The Back End:
Instruction Selection (continued)

- In the code in the previous slide, a straightforward approach has been used to rewrite the IR.
- The values are loaded into registers, the the multiplication operations are performed, and the result is stored in the memory location for `a`.
- The compiler assumes there is an unlimited supply of registers, which it names symbolically.
- Implicitly, the instruction selector relies on the register allocator to map these *virtual registers* to the actual registers of the target machine.

The Back End: Register Allocation

- The instruction selector deliberately ignores the fact that the target machine has a limited set of registers.
- In practice, the earlier stages of compilation may create more demand for registers than the hardware can support.
- It is the job of the register allocator to map the virtual registers to actual registers on the target machine.
- On the following slide is our previous example, rewritten to minimize register use.

The Back End: Register Allocation (continued)

- Rewritten for the ILOC virtual machine:

```
loadAI   r_arp, @a ⇒ r_1 // load 'a'
add      r_1, r_1  ⇒ r_1 // r_1 = a * 2
loadAI   r_arp, @b ⇒ r_2 // load 'b'
mult     r_1, r_2  ⇒ r_1 // r_1 = (a * 2) * b
loadAI   r_arp, @c ⇒ r_2 // load 'c'
mult     r_1, r_2  ⇒ r_1 // r_1 = (a * 2 * b) * c
storeAI  r_1       ⇒ r_arp,@a // write r_1 back to
                              // 'a'
```

- This sequence uses 3 registers instead of 6.

The Back End: Instruction Scheduling

- To increase performance the operations may be reordered to reflect the performance constraints of the target machine.
- **i.e.** memory access operations may take hundreds of cycles, while arithmetic operations may take only several
- For example, assume `loadAI` and `storeAI` take 3 cycles, and `mult` takes 2 cycles to complete.
- Following is a demonstration of how reordering operations improves performance.

The Back End: Instruction Scheduling

Start	End	
1	3	loadAI r_{arp}, @a ⇒ r_1 // load 'a'
4	4	add r_1, r_1 ⇒ r_1 // r_1 = a * 2
5	7	loadAI r_{arp}, @b ⇒ r_2 // load 'b'
8	9	mult r_1, r_2 ⇒ r_1 // r_1 = (a * 2) * b
10	12	loadAI r_{arp}, @c ⇒ r_2 // load 'c'
13	14	mult r_1, r_2 ⇒ r_1 // r_1 = (a * 2 * b) * c
15	17	storeAI r_1 ⇒ r_{arp},@a // write r_1 back to 'a'

- These 8 operations take 17 cycles to complete

The Back End: Instruction Scheduling

Start	End	
1	3	loadAI r_{arp}, @a ⇒ r_1 // load 'a'
2	4	loadAI r_{arp}, @b ⇒ r_2 // load 'b'
3	5	loadAI r_{arp}, @c ⇒ r_3 // load 'c'
4	4	add r_1, r_1 ⇒ r_1 // r_1 = a * 2
5	6	mult r_1, r_2 ⇒ r_1 // r_1 = (a * 2) * b
7	8	mult r_1, r_2 ⇒ r_1 // r_1 = (a * 2 * b) * c
9	11	storeAI r_1 ⇒ r_{arp},@a // write r_1 back to 'a'

- These 8 operations take 11 cycles to complete

The Back End:
Interactions Among Code-Generation Components

- Code generation is complicated further by the interaction of complex problems.
- For example, instruction scheduling moves load operations away from the arithmetic operations that depend on them.
- This increases the amount of time that these registers hold values, and therefore may increase the number of registers needed.
- Also, a false dependency can be created between operations when specific registers are used.

Summary

- Compiler design is a complicated task.
- Compilers use many methods to address a variety of complex problems.
- Many of these problems are too hard to solve optimally, so compilers use approximations and heuristics.
- This often results in interactions that may produce surprising results - which may be good or bad.

Sources

All material included in these slides is from:

Engineering A Compiler, 2nd Edition

by Keith Cooper and Linda Torczan, pgs 1 - 21

FIN