Introduction

CS 1622 Compiler Design

Wonsun Ahn

Instructor Introduction

My Technical Background

- Wonsun Ahn
  - First name is pronounced *one-sun* (if you can manage)
  - Or you can just call me Dr. Ahn (rhymes with *naan*)
- PhD in CPU Design and Compilers
  - University of Illinois at Urbana Champaign
- Industry Experience
  - Bluebird Corporation
    - Built software stack based on Windows Embedded
  - IBM Research (thousands of people)
    - Built supercomputers for ease of parallel programming
- Current interests
  - Compilation for scripting languages / quantum computing

Why Learn Compilers?

Why Learn Compilers?

- Allows you to write more robust, more efficient programs
  - Deeper understanding of compiler errors
  - Deeper understanding of generated code / performance

- Allows you to design your own Domain Specific Language
  - E.g. a new database query language
  - E.g. a new language for musical notations

- Compiler analysis techniques can be used for other purposes
  - E.g. a code analysis tool that finds security vulnerabilities
  - E.g. convert one language to another language

Two Ways to Execute a Program

```
int main()
{
   int x = 1, y = 1, z;
   z = x + y;
   printf("z = %d\n", z);
   return 0;
}
```

- Using an interpreter – interpret and execute line by line
- Using a compiler – translate to machine code, and then run

What is a Compiler?

What is an Interpreter?

- Interpreter: A program that executes source code on the target machine by interpreting it **line by line**

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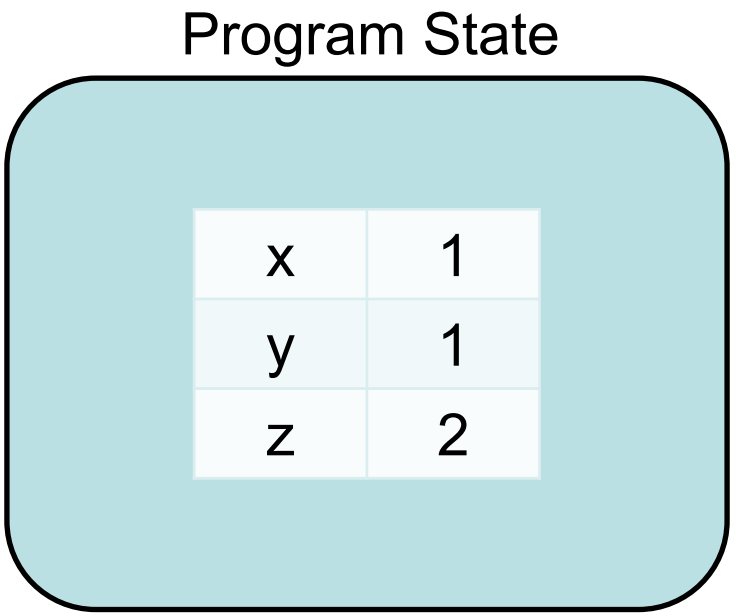
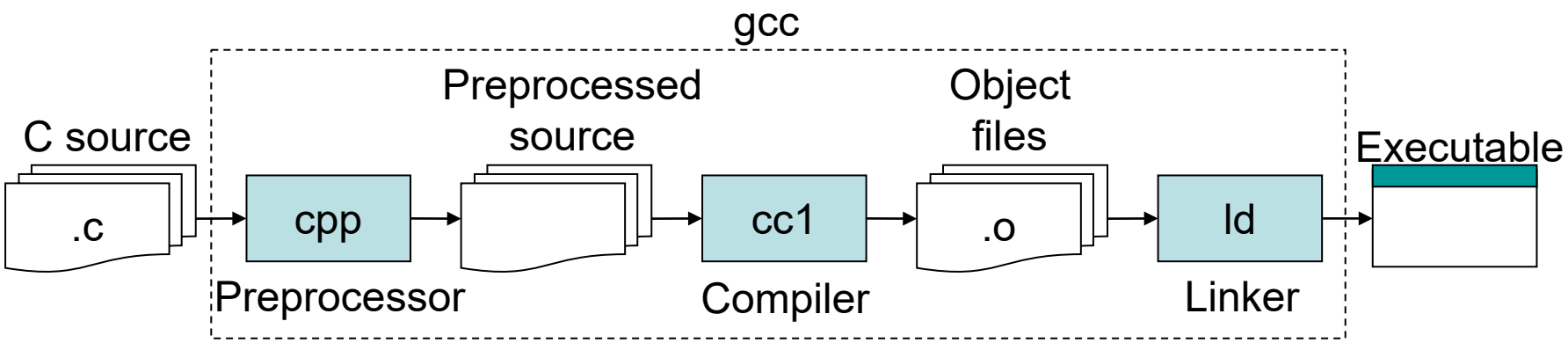


What is an Interpreter?

- Interpreter: A program that executes source code on the target machine by interpreting it **line by line**
  - \+ More portable than compiler
    - Machine code is tied to a specific machine architecture
    - Source code can run anywhere with correct interpreter
  - \+ Relatively simpler to implement than compiler
    - Popular for languages with small user base
  - – Much slower compared to binary execution
    - Source line interpreted on each execution (even in loop)

What is a Compiler?

- Compiler: A program that **translates** **source code** written in one language to a **target code** written in another language
- Source code: Input to compiler
  - Typically a program written in human readable language (e.g. C)
- Target code: Output of compiler
  - Typically binary code written in machine language
    - Native machines: x86, ARM, MIPS code
    - Virtual machines: Java bytecode, LLVM bitcode



What is a Compiler?

- Compiler: A program that **translates** **source code** written in one language to a **target code** written in another language
  - – Less portable than interpreter
    - Machine code is tied to a specific machine architecture
  - – Relatively complex to implement
    - Need a big user base to expend the engineering effort
  - \+ Much faster compared to interpretation
    - No interpretation needed during execution
    - Machine code can be optimized to be even faster

Just-In-Time (JIT) Compiler

- Just-In-Time (JIT) Compiler: A compiler that performs translation at **runtime** (just in time before execution)
  - Traditional compilers are called Ahead-Of-Time (AOT)

AOT vs. JIT Compilation

Ahead-Of-Time (AOT) Compilation

Compile

Binary → Distribute → Binary / Hardware

Languages:

Fortran SOURCE

Just-In-Time (JIT) Compilation

Translate/Minify

Bytecode/Source → Distribute → Bytecode/Source / JIT Compiler / Hardware

Languages:

C#.net Microsoft

OpenCL

Just-In-Time (JIT) Compiler

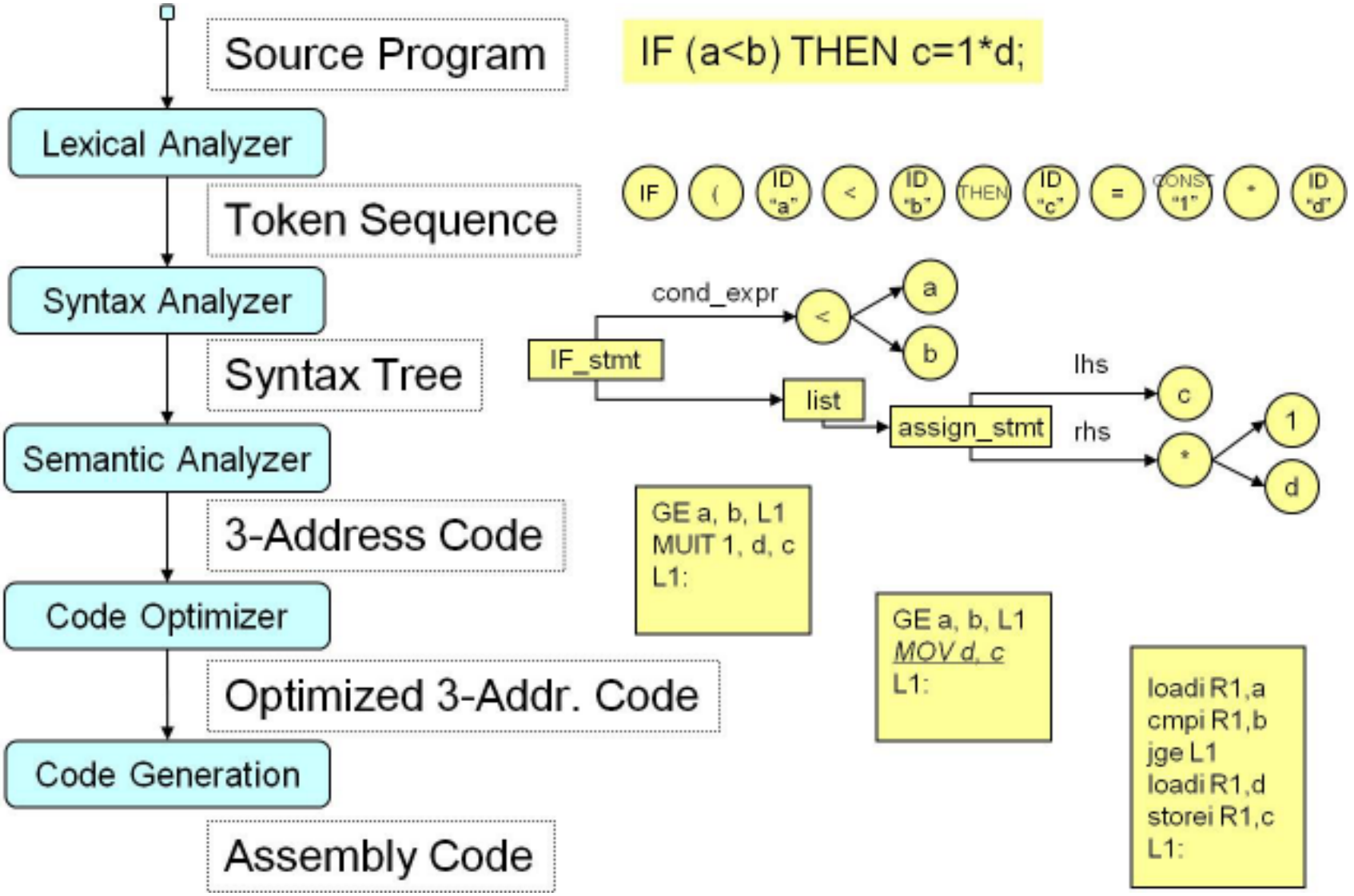
- Just-In-Time (JIT) Compiler: A compiler that performs translation at **runtime** (just in time before execution)
- Pros / Cons compared to AOT compiler
  - + As portable as interpreter
    - Code can run anywhere where there is a JIT compiler
  - + Almost as fast as (sometimes faster) than AOT compiler
    - Slight overhead due to JIT compilation time
    - But can sometimes produce better code than AOT
      - – By profiling program behavior and optimizing
      - – By tailoring code to underlying target machine

In this Class …

- We will learn about how compilers are built in general
- Concepts we will learn applies to both AOT and JIT compilers

Topics Covered

Compiler Phases



Front End

- Group of phases that **analyzes** the source code and builds one or more internal representations (IRs) out of that analysis
  - Comprised of lexical, syntax, and semantic analyses
  - IRs can be syntax trees, 3-address codes, etc.

- **Lexical Analysis**
  - Input: Source code text
  - Output: Sequence of tokens (smallest units with meaning)
    - Tokens: Identifiers, keywords, constants, operators …
  - Scans text left to right and generates tokens one by one, using language token definitions
  - Also checks for illegal tokens (e.g. malformed identifier)

Front End

- **Syntax Analysis**
  - Input: Sequence of tokens
  - Output: Syntax tree
  - Adds tokens to a hierarchical structure called a syntax tree that represents program, using language grammar rules
  - Also checks for syntax errors (e.g. malformed if statement)
- **Semantic Analysis**
  - Input: Syntax tree
  - Output: Low-level IR (e.g. 3-address code)
  - Associates variable uses with variable definitions
  - Generates an IR easily translatable to machine code
  - Also checks for semantic errors (e.g. undefined variable)

Back End

- Group of phases that **synthesizes** machine code from the internal representations (IRs) generated by the front end
  - Comprised of code optimization and code generation

- **Code Optimization**
  - Input: Low-level IR (e.g. 3-address code)
  - Output: (optimized) Low-level IR
  - Modifies IR so that code runs faster and uses less memory
  - Comprised of multiple optimizations applied in sequence
  - Typically same IR format kept before and after
    - So that optimizations can be done in any sequence

Back End

- **Code Generation**
  - Input: (Optimized) low-level IR
  - Output: Target Code
  - Perform following tasks to transform IR to target code:
    - Instruction Selection – select actual machine ISA instructions to implement computation in IR
    - Register Allocation – allocate frequently used locations in CPU registers to speedup access
- An additional code optimization phase may follow code generation to apply target machine specific optimizations

Multiple Front Ends and Back Ends

- Modern compilers typically have multiple front ends
  - E.g. GCC (GNU Compiler Collection) has front ends for C, C++, Fortran, and Java among others
  - All front ends generate the same *common IR* format
- Modern compilers typically have multiple back ends
  - E.g. GCC has back ends for x86, ARM, SPARC, etc.
  - Each back end translate *common IR* to respective target
- A *common IR* is central in enabling this diversity
  - Instead of M X N implementations for M languages and N machines, only need M + N implementations

Challenges Facing Compilers

Challenges Facing Compilers Today

- Fundamental changes are happening in the computing stack that are putting new pressures on the compiler
- Changes in *computer hardware design* is producing new challenges in the back end of the compiler
- Changes in the *programming environment* is producing new challenges in the front end of the compiler

Back End Challenges

- Limits in device miniaturization is driving a sea change in HW
  - CPU frequencies scale no more due to power wall
  - CPUs are less reliable due to transistor doping variability
- Performance must come from **parallelism**
  - Must run code in parallel to make up for lack of freq. scaling
  - Challenge: Automatically parallelize or vectorize code
- Processor efficiency must come from **heterogeneous** architectures
  - Different types of processors on chip for different types of code (e.g. CPUs, GPGPUs, Accelerators, etc …)
  - Challenge: Generating code for this type of architecture
- Memory efficiency must come from **software managed memory**
  - HW manages caches in a reactive manner: not efficient enough
  - Challenge: Generating code that manages caches in software using knowledge of program provided by programmer or analysis

Front End Challenges

- Explosive use of **scripting languages** (JavaScript, Python, R…)
  - Very flexible by design. E.g. Dynamic Typing:

```
var x = 1, y, z;
if (…) y = 2; else y = “2”;
z = x + y; // z == 3 or z == “12”
```

  - Challenge: Generating efficient code for such languages
- New emerging applications such as **deep learning**
  - Different behavior compared to traditional apps
  - Challenge: Optimizing app using semantics of deep learning
- Increasingly complex software ➔ increasingly **complex bugs**
  - Most insidious are heisenbugs (particularly data races)
  - Challenge: Removing or detecting bugs through code analysis
- Increasingly sophisticated **security exploits**
  - Side-channel attacks (e.g. Spectre / Meltdown exploit)
  - Challenge: Protecting generated code from vulnerabilities