# Introduction to Compilers and Language Design

Prof. Douglas Thain University of Notre Dame DRAFT September 14, 2018

#### Introduction to Compilers and Language Design

Copyright (C) 2017 Douglas Thain. All rights reserved.

Anyone is free to download and print the PDF edition of this book for personal use. Commercial distribution, printing, or reproduction without the author's consent is expressly prohibited.

You can find the latest version of the PDF edition, and purchase inexpensive hardcover copies at this website:

http://compilerbook.org

Draft version: September 14, 2018

Sic transit gloria mundi.

#### **Contributions**

I am grateful to the following people for their contributions to this book:

Andrew Litteken drafted the chapter on ARM assembly; Kevin Latimer drew the RegEx to NFA and the LR example figures; Benjamin Gunning fixed an error in LL(1) parse table construction; Tim Shaffer completed the detailed LR(1) example.

And the following people corrected typos: John Westhoff (25), Gonzalo Martinez (25), Daniel Kerrigan (24), Brian DuSell (23), Ryan Mackey (20), Joseph Kimlinger (12), Andrew Litteken (9), Thomas Cane (9), Luis Prieb (7), Jonathan Xu (6), John Johnson (4), Yaoxian Qu (2). Maria Aranguren (2), Patrick Lacher (2), Connor Higgins

(2), Benjamin Gunning (1) Charles Osborne (1), William Theisen (1), Jessica Cioffi (1), Ben Tovar (1), Ryan Michalec (1),

Please send any comments or corrections via email to Prof. Douglas Thain (dthain@nd.edu).

CONTENTS vii

### **Contents**

1	Intro	oduction	1
	1.1	What is a compiler?	1
	1.2	Why should you study compilers?	2
	1.3	What's the best way to learn about compilers?	2
	1.4	What language should I use?	2
	1.5	How is this book different from others?	3
	1.6	What other books should I read?	4
2	A Q	uick Tour	5
	2.1	The Compiler Toolchain	5
	2.2	Stages Within a Compiler	6
	2.3	Example Compilation	7
	2.4	Exercises	10
3	Scar	uning 1	1
	3.1	Kinds of Tokens	1
	3.2	A Hand-Made Scanner	12
	3.3	Regular Expressions	13
	3.4		15
		3.4.1 Deterministic Finite Automata	16
			17
	3.5	Conversion Algorithms	19
		3.5.1 Converting REs to NFAs	19
			22
			24
	3.6	Limits of Finite Automata	26
	3.7	Using a Scanner Generator	26
	3.8	Practical Considerations	29
	3.9	Exercises	31
	3.10	Further Reading	33
4	Pars	ing 3	35
	4.1	Overview	35
	4.2	Context Free Grammars	35

viii CONTENTS

4.2.1 Deriving Sentences 4.2.2 Ambiguous Grammars 4.3 LL Grammars 4.3.1 Eliminating Left Recursion 4.3.2 Eliminating Common Left Prefixes 4.3.3 First and Follow Sets 4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading  6 The Abstract Syntax Tree	ing Left Recursion	37 40
4.3 LL Grammars 4.3.1 Eliminating Left Recursion 4.3.2 Eliminating Common Left Prefixes 4.3.3 First and Follow Sets 4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading	ing Left Recursion	40
4.3.1 Eliminating Left Recursion 4.3.2 Eliminating Common Left Prefixes 4.3.3 First and Follow Sets 4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading	ing Left Recursion	
4.3.2 Eliminating Common Left Prefixes 4.3.3 First and Follow Sets 4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading	ing Common Left Prefixes	40
4.3.2 Eliminating Common Left Prefixes 4.3.3 First and Follow Sets 4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading	ing Common Left Prefixes	
4.3.3 First and Follow Sets 4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading	Follow Sets	
4.3.4 Recursive Descent Parsing 4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading		
4.3.5 Table Driven Parsing 4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading		
4.4 LR Grammars 4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading		
4.4.1 Shift-Reduce Parsing 4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading		
4.4.2 The LR(0) Automaton 4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading		
4.4.3 SLR Parsing 4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading  6 The Abstract Syntax Tree		
4.4.4 LR(1) Parsing 4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading  6 The Abstract Syntax Tree		
4.4.5 LALR Parsing 4.5 Grammar Classes Revisited 4.6 The Chomsky Hierarchy 4.7 Exercises 4.8 Further Reading  5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading  6 The Abstract Syntax Tree		
<ul> <li>4.5 Grammar Classes Revisited</li> <li>4.6 The Chomsky Hierarchy</li> <li>4.7 Exercises</li> <li>4.8 Further Reading</li> <li>5 Parsing in Practice</li> <li>5.1 The Bison Parser Generator</li> <li>5.2 Expression Validator</li> <li>5.3 Expression Interpreter</li> <li>5.4 Expression Trees</li> <li>5.5 Exercises</li> <li>5.6 Further Reading</li> <li>6 The Abstract Syntax Tree</li> </ul>		
<ul> <li>4.6 The Chomsky Hierarchy</li> <li>4.7 Exercises</li> <li>4.8 Further Reading</li> <li>5 Parsing in Practice</li> <li>5.1 The Bison Parser Generator</li> <li>5.2 Expression Validator</li> <li>5.3 Expression Interpreter</li> <li>5.4 Expression Trees</li> <li>5.5 Exercises</li> <li>5.6 Further Reading</li> <li>6 The Abstract Syntax Tree</li> </ul>		
<ul> <li>4.7 Exercises</li> <li>4.8 Further Reading</li> <li>5 Parsing in Practice</li> <li>5.1 The Bison Parser Generator</li> <li>5.2 Expression Validator</li> <li>5.3 Expression Interpreter</li> <li>5.4 Expression Trees</li> <li>5.5 Exercises</li> <li>5.6 Further Reading</li> <li>6 The Abstract Syntax Tree</li> </ul>		
4.8 Further Reading		
5 Parsing in Practice 5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading 6 The Abstract Syntax Tree		
5.1 The Bison Parser Generator 5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading 6 The Abstract Syntax Tree	;	00
5.2 Expression Validator 5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading 6 The Abstract Syntax Tree		67
5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading 6 The Abstract Syntax Tree	r Generator	68
5.3 Expression Interpreter 5.4 Expression Trees 5.5 Exercises 5.6 Further Reading 6 The Abstract Syntax Tree	dator	71
5.4       Expression Trees		
<ul><li>5.5 Exercises</li><li>5.6 Further Reading</li><li>6 The Abstract Syntax Tree</li></ul>		
<ul><li>5.6 Further Reading</li></ul>		
6 The Abstract Syntax Tree		
	,	
(1 0 :		83
6.1 Overview		83
6.2 Declarations		84
6.3 Statements		86
6.4 Expressions		88
6.5 Types		90
6.6 Putting it All Together		
	Ť	
0.7 Dunding the AST		
		97
<ul><li>6.8 Exercises</li></ul>	pe Systems	
6.8 Exercises	oe System	101
<ul> <li>6.8 Exercises</li></ul>	pe System	104
<ul> <li>6.8 Exercises</li></ul>	le	105
<ul> <li>6.8 Exercises</li></ul>		
<ul> <li>6.8 Exercises</li></ul>		
<ul> <li>6.8 Exercises</li></ul>		111

CONTENTS ix

	7.8	Exercises
	7.9	Further Reading
		O Company of the comp
8	Inte	rmediate Representations 117
	8.1	Introduction
	8.2	Abstract Syntax Tree
	8.3	Directed Acyclic Graph
	8.4	Control Flow Graph
	8.5	Static Single Assignment Form
	8.6	Linear IR
	8.7	Stack Machine IR
	8.8	Examples
	0.0	8.8.1 GIMPLE - GNU Simple Representation
		8.8.2 LLVM - Low Level Virtual Machine
		8.8.3 JVM - Java Virtual Machine
	8.9	Exercises
		Further Reading
	0.10	Tuttlet Reading
9	Men	nory Organization 133
	9.1	Introduction
	9.2	Logical Segmentation
	9.3	Heap Management
	9.4	Stack Management
	7.1	9.4.1 Stack Calling Convention
		9.4.2 Register Calling Convention
	9.5	Locating Data
	9.6	Program Loading
	9.7	Further Reading
	9.7	ruttler Reading
10	Asse	embly Language 147
		Introduction
		Open Source Assembler Tools
		X86 Assembly Language
	10.0	10.3.1 Registers and Data Types
		10.3.2 Addressing Modes
		10.3.3 Basic Arithmetic
		10.3.4 Comparisons and Jumps
		10.3.5 The Stack
		10.3.6 Calling a Function
		10.3.7 Defining a Leaf Function
		10.3.8 Defining a Complex Function
	10.4	ARM Assembly
		10.4.1 Registers and Data Types
		10.4.2 Addressing Modes
		10.4.3 Basic Arithmetic

x CONTENTS

	10.4.4 Comparisons and Branches	169
	10.4.5 The Stack	171
	10.4.6 Calling a Function	172
	10.4.7 Defining a Leaf Function	173
	10.4.8 Defining a Complex Function	174
	10.4.9 64-bit Differences	177
	10.5 Further Reading	178
11	Code Generation	179
	11.1 Introduction	179
	11.2 Supporting Functions	179
	11.3 Generating Expressions	
	11.4 Generating Statements	
	11.5 Conditional Expressions	
	11.6 Generating Declarations	
	11.7 Exercises	
12	Optimization	193
	12.1 Overview	
	12.2 Optimization in Perspective	
	12.3 High Level Optimizations	
	12.3.1 Constant Folding	
	12.3.2 Strength Reduction	
	12.3.3 Loop Unrolling	
	12.3.4 Code Hoisting	
	12.3.5 Function Inlining	
	12.3.6 Dead Code Detection and Elimination	
	12.4 Low-Level Optimizations	
	12.4.1 Peephole Optimizations	
	12.4.2 Instruction Selection	202
	12.5 Register Allocation	
	12.5.1 Safety of Register Allocation	
	12.5.2 Priority of Register Allocation	
	12.5.3 Conflicts Between Variables	
	12.5.4 Global Register Allocation	
	12.6 Optimization Pitfalls	
	12.7 Optimization Interactions	
	12.8 Exercises	212
	12.9 Further Reading	213
A	Sample Course Project	215
-	A.1 Scanner Assignment	
	A.2 Parser Assignment	
	A.3 Pretty-Printer Assignment	
	A.4 Typechecker Assignment	

CONTENTS xi

	A.6	Optional: Intermediate Representation	216
В	The	C-Minor Language	219
	B.1	Overview	219
	B.2	Tokens	219
	B.3	Types	220
	<b>B.4</b>	Expressions	221
	B.5	Declarations and Statements	222
	B.6	Functions	222
	B.7	Optional Elements	223
C	Cod	ing Conventions	225

xii CONTENTS

LIST OF FIGURES xiii

## **List of Figures**

2.1	A Typical Compiler Toolchain	5
2.2	The Stages of a Unix Compiler	6
2.3	Example AST	9
2.4	Example Intermediate Representation	9
2.5	Example Assembly Code	10
3.1	A Simple Hand Made Scanner	12
3.2	Relationship Between REs, NFAs, and DFAs	19
3.3	Subset Construction Algorithm	22
3.4	Converting an NFA to a DFA via Subset Construction	23
3.5	Hopcroft's DFA Minimization Algorithm	24
3.6	Structure of a Flex File	27
3.7	Example Flex Specification	28
3.8	Example Main Program	28
3.9	Example Token Enumeration	29
3.10	Build Procedure for a Flex Program	30
5.10	bund Procedure for a rick Program	50
4.1	Two Derivations of the Same Sentence	38
4.2	A Recursive-Descent Parser	45
4.3	$LR(0)$ Automaton for Grammar $G_{10}$	52
4.4	SLR Parse Table for Grammar $G_{10}$	55
4.5	Part of LR(0) Automaton for Grammar $G_{11}$	58
4.6	LR(1) Automaton for Grammar $G_{10}$	60
4.7	The Chomsky Hierarchy	63
5.1	Picon Charification for Eugenosian Validator	69
5.2	Bison Specification for Expression Validator	70
5.3	Main Program for Expression Validator	70
5.4	Build Procedure for Bison and Flex Together	73
5.5	Bison Specification for an Interpreter	73 74
5.6	AST for Expression Interpreter	74
5.7	Building an AST for the Expression Grammar	78
5.8	Evaluating Expressions	70 79
3.0	Printing and Evaluating Expressions	19
7.1	The Symbol Structure	105

7.2	A Nested Symbol Table
7.3	Symbol Table API
7.4	Name Resolution for Declarations
7.5	Name Resolution for Expressions
8.1	Sample DAG Data Structure Definition
8.2	Example of Constant Folding
8.3	Example Control Flow Graph
9.1	Flat Memory Model
9.2	Logical Segments
9.3	Multiprogrammed Memory Layout
10.1	X86 Register Structure
	X86 Register Structure
10.3	Summary of System V ABI Calling Convention 158
10.4	System V ABI Register Assignments 160
10.5	Example X86-64 Stack Layout
10.6	Complete X86 Example
10.7	ARM Addressing Modes
10.8	ARM Branch Instructions
10.9	Summary of ARM-Thumb Procedure Call Standard 172
10.10	OARM Register Assignments
10.11	Example ARM Stack Frame
	Complete ARM Example
11.1	Code Generation Functions
11.2	Example of Generating X86 Code from a DAG 182
11.3	Expression Generation Skeleton
11.4	Generating Code for a Function Call
11.5	Statement Generator Skeleton
12.1	Timing a Fast Operation
12.2	Constant Folding Pseudo-Code
	Example X86 Instruction Templates
12.4	Example of Tree Rewriting
12.5	Live Ranges and Register Conflict Graph 208
12.6	Example of Global Register Allocation 209