

Contents

1	Introduction	1
1.1	What is a compiler?	1
1.2	The phases of a compiler	2
1.3	Interpreters	3
1.4	Why learn about compilers?	4
1.5	The structure of this book	5
1.6	To the lecturer	6
1.7	Acknowledgements	7
1.8	Permission to use	7
2	Lexical Analysis	9
2.1	Introduction	9
2.2	Regular expressions	10
2.2.1	Shorthands	13
2.2.2	Examples	14
2.3	Nondeterministic finite automata	15
2.4	Converting a regular expression to an NFA	18
2.4.1	Optimisations	20
2.5	Deterministic finite automata	22
2.6	Converting an NFA to a DFA	23
2.6.1	Solving set equations	23
2.6.2	The subset construction	26
2.7	Size versus speed	29
2.8	Minimisation of DFAs	30
2.8.1	Example	32
2.8.2	Dead states	34
2.9	Lexers and lexer generators	35
2.9.1	Lexer generators	41
2.10	Properties of regular languages	42
2.10.1	Relative expressive power	42
2.10.2	Limits to expressive power	44

2.10.3	Closure properties	45
2.11	Further reading	46
	Exercises	46
3	Syntax Analysis	53
3.1	Introduction	53
3.2	Context-free grammars	54
3.2.1	How to write context free grammars	56
3.3	Derivation	58
3.3.1	Syntax trees and ambiguity	60
3.4	Operator precedence	63
3.4.1	Rewriting ambiguous expression grammars	64
3.5	Other sources of ambiguity	66
3.6	Syntax analysis	68
3.7	Predictive parsing	68
3.8	<i>Nullable</i> and <i>FIRST</i>	69
3.9	Predictive parsing revisited	73
3.10	<i>FOLLOW</i>	74
3.11	A larger example	77
3.12	LL(1) parsing	79
3.12.1	Recursive descent	80
3.12.2	Table-driven LL(1) parsing	81
3.12.3	Conflicts	82
3.13	Rewriting a grammar for LL(1) parsing	84
3.13.1	Eliminating left-recursion	84
3.13.2	Left-factorisation	86
3.13.3	Construction of LL(1) parsers summarized	87
3.14	SLR parsing	88
3.15	Constructing SLR parse tables	90
3.15.1	Conflicts in SLR parse-tables	94
3.16	Using precedence rules in LR parse tables	95
3.17	Using LR-parser generators	98
3.17.1	Declarations and actions	99
3.17.2	Abstract syntax	99
3.17.3	Conflict handling in parser generators	102
3.18	Properties of context-free languages	104
3.19	Further reading	105
	Exercises	105

4	Scopes and Symbol Tables	113
4.1	Introduction	113
4.2	Symbol tables	114
4.2.1	Implementation of symbol tables	115
4.2.2	Simple persistent symbol tables	115
4.2.3	A simple imperative symbol table	117
4.2.4	Efficiency issues	117
4.2.5	Shared or separate name spaces	118
4.3	Further reading	118
	Exercises	118
5	Interpretation	121
5.1	Introduction	121
5.2	The structure of an interpreter	122
5.3	A small example language	122
5.4	An interpreter for the example language	124
5.4.1	Evaluating expressions	124
5.4.2	Interpreting function calls	126
5.4.3	Interpreting a program	128
5.5	Advantages and disadvantages of interpretation	128
5.6	Further reading	130
	Exercises	130
6	Type Checking	133
6.1	Introduction	133
6.2	The design space of types	133
6.3	Attributes	135
6.4	Environments for type checking	135
6.5	Type checking expressions	136
6.6	Type checking of function declarations	138
6.7	Type checking a program	139
6.8	Advanced type checking	140
6.9	Further reading	143
	Exercises	143
7	Intermediate-Code Generation	147
7.1	Introduction	147
7.2	Choosing an intermediate language	148
7.3	The intermediate language	150
7.4	Syntax-directed translation	151
7.5	Generating code from expressions	152
7.5.1	Examples of translation	155

7.6	Translating statements	156
7.7	Logical operators	159
7.7.1	Sequential logical operators	160
7.8	Advanced control statements	164
7.9	Translating structured data	165
7.9.1	Floating-point values	165
7.9.2	Arrays	165
7.9.3	Strings	171
7.9.4	Records/structs and unions	171
7.10	Translating declarations	172
7.10.1	Example: Simple local declarations	172
7.11	Further reading	172
	Exercises	173
8	Machine-Code Generation	179
8.1	Introduction	179
8.2	Conditional jumps	180
8.3	Constants	181
8.4	Exploiting complex instructions	181
8.4.1	Two-address instructions	186
8.5	Optimisations	186
8.6	Further reading	188
	Exercises	188
9	Register Allocation	191
9.1	Introduction	191
9.2	Liveness	192
9.3	Liveness analysis	193
9.4	Interference	196
9.5	Register allocation by graph colouring	199
9.6	Spilling	200
9.7	Heuristics	202
9.7.1	Removing redundant moves	205
9.7.2	Using explicit register numbers	205
9.8	Further reading	206
	Exercises	206
10	Function calls	209
10.1	Introduction	209
10.1.1	The call stack	209
10.2	Activation records	210
10.3	Prologues, epilogues and call-sequences	211

10.4	Caller-saves versus callee-saves	213
10.5	Using registers to pass parameters	215
10.6	Interaction with the register allocator	219
10.7	Accessing non-local variables	221
10.7.1	Global variables	221
10.7.2	Call-by-reference parameters	222
10.7.3	Nested scopes	223
10.8	Variants	226
10.8.1	Variable-sized frames	226
10.8.2	Variable number of parameters	227
10.8.3	Direction of stack-growth and position of FP	227
10.8.4	Register stacks	228
10.8.5	Functions as values	228
10.9	Further reading	229
	Exercises	229
11	Analysis and optimisation	231
11.1	Data-flow analysis	232
11.2	Common subexpression elimination	233
11.2.1	Available assignments	233
11.2.2	Example of available-assignments analysis	236
11.2.3	Using available assignment analysis for common subexpression elimination	237
11.3	Jump-to-jump elimination	240
11.4	Index-check elimination	241
11.5	Limitations of data-flow analyses	244
11.6	Loop optimisations	245
11.6.1	Code hoisting	245
11.6.2	Memory prefetching	246
11.7	Optimisations for function calls	248
11.7.1	Inlining	249
11.7.2	Tail-call optimisation	250
11.8	Specialisation	252
11.9	Further reading	254
	Exercises	254
12	Memory management	257
12.1	Introduction	257
12.2	Static allocation	257
12.2.1	Limitations	258
12.3	Stack allocation	258

12.4	Heap allocation	259
12.5	Manual memory management	259
12.5.1	A simple implementation of <code>malloc()</code> and <code>free()</code>	260
12.5.2	Joining freed blocks	263
12.5.3	Sorting by block size	264
12.5.4	Summary of manual memory management	265
12.6	Automatic memory management	266
12.7	Reference counting	266
12.8	Tracing garbage collectors	268
12.8.1	Scan-sweep collection	269
12.8.2	Two-space collection	271
12.8.3	Generational and concurrent collectors	273
12.9	Summary of automatic memory management	276
12.10	Further reading	277
	Exercises	277
13	Bootstrapping a compiler	281
13.1	Introduction	281
13.2	Notation	281
13.3	Compiling compilers	283
13.3.1	Full bootstrap	285
13.4	Further reading	288
	Exercises	288
A	Set notation and concepts	291
A.1	Basic concepts and notation	291
A.1.1	Operations and predicates	291
A.1.2	Properties of set operations	292
A.2	Set-builder notation	293
A.3	Sets of sets	294
A.4	Set equations	295
A.4.1	Monotonic set functions	295
A.4.2	Distributive functions	296
A.4.3	Simultaneous equations	297
	Exercises	297

List of Figures

2.1	Regular expressions	11
2.2	Some algebraic properties of regular expressions	14
2.3	Example of an NFA	17
2.4	Constructing NFA fragments from regular expressions	19
2.5	NFA for the regular expression $(a b)^*ac$	20
2.6	Optimised NFA construction for regular expression shorthands . .	21
2.7	Optimised NFA for $[0-9]^+$	21
2.8	Example of a DFA	22
2.9	DFA constructed from the NFA in figure 2.5	29
2.10	Non-minimal DFA	32
2.11	Minimal DFA	34
2.12	Combined NFA for several tokens	38
2.13	Combined DFA for several tokens	39
2.14	A 4-state NFA that gives 15 DFA states	44
3.1	From regular expressions to context free grammars	56
3.2	Simple expression grammar	57
3.3	Simple statement grammar	57
3.4	Example grammar	59
3.5	Derivation of the string aabbbcc using grammar 3.4	59
3.6	Leftmost derivation of the string aabbbcc using grammar 3.4 . .	59
3.7	Syntax tree for the string aabbbcc using grammar 3.4	61
3.8	Alternative syntax tree for the string aabbbcc using grammar 3.4 .	61
3.9	Unambiguous version of grammar 3.4	62
3.10	Preferred syntax tree for $2+3*4$ using grammar 3.2	63
3.11	Unambiguous expression grammar	66
3.12	Syntax tree for $2+3*4$ using grammar 3.11	67
3.13	Unambiguous grammar for statements	68
3.14	Fixed-point iteration for calculation of <i>Nullable</i>	71
3.15	Fixed-point iteration for calculation of <i>FIRST</i>	72
3.16	Recursive descent parser for grammar 3.9	81

3.17	LL(1) table for grammar 3.9	82
3.18	Program for table-driven LL(1) parsing	83
3.19	Input and stack during table-driven LL(1) parsing	83
3.20	Removing left-recursion from grammar 3.11	85
3.21	Left-factorised grammar for conditionals	87
3.22	SLR table for grammar 3.9	90
3.23	Algorithm for SLR parsing	91
3.24	Example SLR parsing	91
3.25	Example grammar for SLR-table construction	92
3.26	NFAs for the productions in grammar 3.25	92
3.27	Epsilon-transitions added to figure 3.26	93
3.28	SLR DFA for grammar 3.9	94
3.29	Summary of SLR parse-table construction	95
3.30	Textual representation of NFA states	103
5.1	Example language for interpretation	123
5.2	Evaluating expressions	125
5.3	Evaluating a function call	127
5.4	Interpreting a program	128
6.1	The design space of types	134
6.2	Type checking of expressions	137
6.3	Type checking a function declaration	139
6.4	Type checking a program	141
7.1	The intermediate language	150
7.2	A simple expression language	152
7.3	Translating an expression	154
7.4	Statement language	156
7.5	Translation of statements	158
7.6	Translation of simple conditions	159
7.7	Example language with logical operators	161
7.8	Translation of sequential logical operators	162
7.9	Translation for one-dimensional arrays	166
7.10	A two-dimensional array	168
7.11	Translation of multi-dimensional arrays	169
7.12	Translation of simple declarations	173
8.1	Pattern/replacement pairs for a subset of the MIPS instruction set	185
9.1	Gen and kill sets	194
9.2	Example program for liveness analysis and register allocation	195

9.3	<i>succ</i> , <i>gen</i> and <i>kill</i> for the program in figure 9.2	196
9.4	Fixed-point iteration for liveness analysis	197
9.5	Interference graph for the program in figure 9.2	198
9.6	Algorithm 9.3 applied to the graph in figure 9.5	202
9.7	Program from figure 9.2 after spilling variable <i>a</i>	203
9.8	Interference graph for the program in figure 9.7	203
9.9	Colouring of the graph in figure 9.8	204
10.1	Simple activation record layout	211
10.2	Prologue and epilogue for the frame layout shown in figure 10.1	212
10.3	Call sequence for $x := \text{CALL } f(a_1, \dots, a_n)$ using the frame layout shown in figure 10.1	213
10.4	Activation record layout for callee-saves	214
10.5	Prologue and epilogue for callee-saves	214
10.6	Call sequence for $x := \text{CALL } f(a_1, \dots, a_n)$ for callee-saves	215
10.7	Possible division of registers for 16-register architecture	216
10.8	Activation record layout for the register division shown in figure 10.7	216
10.9	Prologue and epilogue for the register division shown in figure 10.7	217
10.10	Call sequence for $x := \text{CALL } f(a_1, \dots, a_n)$ for the register division shown in figure 10.7	218
10.11	Example of nested scopes in Pascal	223
10.12	Adding an explicit frame-pointer to the program from figure 10.11	224
10.13	Activation record with static link	225
10.14	Activation records for <i>f</i> and <i>g</i> from figure 10.11	225
11.1	Gen and kill sets for available assignments	235
11.2	Example program for available-assignments analysis	236
11.3	<i>pred</i> , <i>gen</i> and <i>kill</i> for the program in figure 11.2	237
11.4	Fixed-point iteration for available-assignment analysis	238
11.5	The program in figure 11.2 after common subexpression elimination	239
11.6	Equations for index-check elimination	242
11.7	Intermediate code for for-loop with index check	244
12.1	Operations on a free list	261