
Contents

| | |
|--|-----------|
| Preface | v |
| 1 An Introduction to Data Flow Analysis | 1 |
| 1.1 A Motivating Example | 1 |
| 1.1.1 Optimizing for Heap Memory | 1 |
| 1.1.2 Computing Liveness | 4 |
| 1.1.3 Computing Aliases | 9 |
| 1.1.4 Performing Optimization | 10 |
| 1.1.5 General Observations | 10 |
| 1.2 Program Analysis: The Larger Perspective | 12 |
| 1.3 Characteristics of Data Flow Analysis | 16 |
| 1.4 Summary and Concluding Remarks | 18 |
| 1.5 Bibliographic Notes | 19 |
| I Intraprocedural Data Flow Analysis | 21 |
| 2 Classical Bit Vector Data Flow Analysis | 23 |
| 2.1 Basic Concepts and Notations | 23 |
| 2.2 Discovering Local Data Flow Information | 24 |
| 2.3 Discovering Global Properties of Variables | 26 |
| 2.3.1 Live Variables Analysis | 26 |
| 2.3.2 Dead Variables Analysis | 29 |
| 2.3.3 Reaching Definitions Analysis | 29 |
| 2.3.4 Reaching Definitions for Copy Propagation | 32 |
| 2.4 Discovering Global Properties of Expressions | 33 |
| 2.4.1 Available Expressions Analysis | 33 |
| 2.4.2 Partially Available Expressions Analysis | 36 |
| 2.4.3 Anticipable Expressions Analysis | 37 |
| 2.4.4 Classical Partial Redundancy Elimination | 39 |
| 2.4.5 Lazy Code Motion | 49 |
| 2.5 Combined <i>May-Must</i> Analyses | 53 |
| 2.6 Summary and Concluding Remarks | 56 |
| 2.7 Bibliographic Notes | 57 |

| | |
|---|------------|
| 3 Theoretical Abstractions in Data Flow Analysis | 59 |
| 3.1 Graph Properties Relevant to Data Flow Analysis | 59 |
| 3.2 Data Flow Framework | 63 |
| 3.2.1 Modeling Data Flow Values Using Lattices | 64 |
| 3.2.2 Modeling Flow Functions | 71 |
| 3.2.3 Data Flow Frameworks | 72 |
| 3.3 Data Flow Assignments | 74 |
| 3.3.1 Meet Over Paths Assignment | 75 |
| 3.3.2 Fixed Point Assignment | 76 |
| 3.3.3 Existence of Fixed Point Assignment | 77 |
| 3.4 Computing Data Flow Assignments | 79 |
| 3.4.1 Computing <i>MFP</i> Assignment | 79 |
| 3.4.2 Comparing <i>MFP</i> and <i>MOP</i> Assignments | 81 |
| 3.4.3 Undecidability of <i>MOP</i> Assignment Computation | 83 |
| 3.5 Complexity of Data Flow Analysis for Rapid Frameworks | 85 |
| 3.5.1 Properties of Data Flow Frameworks | 86 |
| 3.5.2 Complexity for General CFGs | 90 |
| 3.5.3 Complexity in Special Cases | 97 |
| 3.6 Summary and Concluding Remarks | 99 |
| 3.7 Bibliographic Notes | 100 |
| 4 General Data Flow Frameworks | 101 |
| 4.1 Non-Separable Flow Functions | 101 |
| 4.2 Discovering Properties of Variables | 103 |
| 4.2.1 Faint Variables Analysis | 103 |
| 4.2.2 Possibly Uninitialized Variables Analysis | 106 |
| 4.2.3 Constant Propagation | 108 |
| 4.2.4 Variants of Constant Propagation | 115 |
| 4.3 Discovering Properties of Pointers | 119 |
| 4.3.1 Points-To Analysis of Stack and Static Data | 119 |
| 4.3.2 Alias Analysis of Stack and Static Data | 129 |
| 4.3.3 Formulating Data Flow Equations for Alias Analysis | 132 |
| 4.4 Liveness Analysis of Heap Data | 135 |
| 4.4.1 Access Expressions and Access Paths | 137 |
| 4.4.2 Liveness of Access Paths | 138 |
| 4.4.3 Representing Sets of Access Paths by Access Graphs | 141 |
| 4.4.4 Data Flow Analysis for Explicit Liveness | 146 |
| 4.4.5 The Motivating Example Revisited | 151 |
| 4.5 Modeling Entity Dependence | 152 |
| 4.5.1 Primitive Entity Functions | 153 |
| 4.5.2 Composite Entity Functions | 155 |
| 4.6 Summary and Concluding Remarks | 156 |
| 4.7 Bibliographic Notes | 156 |

| | |
|--|------------|
| 5 Complexity of Iterative Data Flow Analysis | 159 |
| 5.1 Generic Flow Functions and Data Flow Equations | 159 |
| 5.2 Generic Round-Robin Iterative Algorithm | 162 |
| 5.3 Complexity of Round-Robin Iterative Algorithm | 164 |
| 5.3.1 Identifying the Core Work Using Work List | 165 |
| 5.3.2 Information Flow Paths in Bit Vector Frameworks | 171 |
| 5.3.3 Defining Complexity Using Information Flow Paths | 173 |
| 5.3.4 Information Flow Paths in Fast Frameworks | 175 |
| 5.3.5 Information Flow Paths in Non-separable Frameworks | 179 |
| 5.4 Summary and Concluding Remarks | 184 |
| 5.5 Bibliographic Notes | 184 |
| 6 Single Static Assignment Form as Intermediate Representation | 185 |
| 6.1 Introduction | 185 |
| 6.1.1 An Overview of SSA | 186 |
| 6.1.2 Benefits of SSA Representation | 188 |
| 6.2 Construction of SSA Form Programs | 189 |
| 6.2.1 Dominance Frontier | 191 |
| 6.2.2 Placement of ϕ -instructions | 194 |
| 6.2.3 Renaming of Variables | 196 |
| 6.2.4 Correctness of the Algorithm | 198 |
| 6.3 Destruction of SSA | 207 |
| 6.3.1 An Algorithm for SSA Destruction | 209 |
| 6.3.2 SSA Destruction and Register Allocation | 216 |
| 6.4 Summary and Concluding Remarks | 227 |
| 6.5 Bibliographic Notes | 228 |
| II Interprocedural Data Flow Analysis | 231 |
| 7 Introduction to Interprocedural Data Flow Analysis | 233 |
| 7.1 A Motivating Example | 233 |
| 7.2 Program Representations for Interprocedural Analysis | 234 |
| 7.3 Modeling Interprocedural Data Flow Analysis | 236 |
| 7.3.1 Summary Flow Functions | 236 |
| 7.3.2 Inherited and Synthesized Data Flow Information | 237 |
| 7.3.3 Approaches to Interprocedural Data Flow Analysis | 238 |
| 7.4 Compromising Precision for Scalability | 239 |
| 7.4.1 Flow and Context Insensitivity | 240 |
| 7.4.2 Side Effects Analysis | 244 |
| 7.5 Language Features Influencing Interprocedural Analysis | 244 |
| 7.6 Common Variants of Interprocedural Data Flow Analysis | 246 |
| 7.6.1 Intraprocedural Analysis with Conservative Interprocedural Approximation | 246 |
| 7.6.2 Intraprocedural Analysis with Side Effects Computation | 248 |
| 7.6.3 Whole Program Analysis | 253 |

| | | |
|------------|--|------------|
| 7.7 | An Aside on Interprocedural Optimizations | 254 |
| 7.8 | Summary and Concluding Remarks | 256 |
| 7.9 | Bibliographic Notes | 256 |
| 8 | Functional Approach to Interprocedural Data Flow Analysis | 259 |
| 8.1 | Side Effects Analysis of Procedure Calls | 259 |
| 8.1.1 | Computing Flow Sensitive Side Effects | 261 |
| 8.1.2 | Computing Flow Insensitive Side Effects | 263 |
| 8.2 | Handling the Effects of Parameters | 266 |
| 8.2.1 | Defining Aliasing of Parameters | 267 |
| 8.2.2 | Formulating Alias Analysis of Parameters | 268 |
| 8.2.3 | Augmenting Data Flow Analyses Using Parameter Aliases | 271 |
| 8.2.4 | Efficient Parameter Alias Analysis | 273 |
| 8.3 | Whole Program Analysis | 274 |
| 8.3.1 | Lattice of Flow Functions | 274 |
| 8.3.2 | Reducing Function Compositions and Confluences | 275 |
| 8.3.3 | Constructing Summary Flow Functions | 278 |
| 8.3.4 | Computing Data Flow Information | 282 |
| 8.3.5 | Enumerating Summary Flow Functions | 285 |
| 8.4 | Summary and Concluding Remarks | 290 |
| 8.5 | Bibliographic Notes | 291 |
| 9 | Value-Based Approach to Interprocedural Data Flow Analysis | 293 |
| 9.1 | Program Model for Value-Based Approaches to Interprocedural Data Flow Analysis | 293 |
| 9.2 | Interprocedural Analysis Using Restricted Contexts | 296 |
| 9.3 | Interprocedural Analysis Using Unrestricted Contexts | 301 |
| 9.3.1 | Using Call Strings to Represent Unrestricted Contexts | 302 |
| 9.3.2 | Issues in Termination of Call String Construction | 305 |
| 9.4 | Bounding Unrestricted Contexts Using Data Flow Values | 311 |
| 9.4.1 | Call String Invariants | 311 |
| 9.4.2 | Value-Based Termination of Call String Construction | 317 |
| 9.5 | The Motivating Example Revisited | 324 |
| 9.6 | Summary and Concluding Remarks | 326 |
| 9.7 | Bibliographic Notes | 328 |
| III | Implementing Data Flow Analysis | 331 |
| 10 | Implementing Data Flow Analysis in GCC | 333 |
| 10.1 | Specifying a Data Flow Analysis | 333 |
| 10.1.1 | Registering a Pass With the Pass Manager in GCC | 334 |
| 10.1.2 | Specifying Available Expressions Analysis | 336 |
| 10.1.3 | Specifying Other Bit Vector Data Flow Analyses | 338 |
| 10.2 | An Example of Data Flow Analysis | 340 |
| 10.2.1 | Executing the Data Flow Analyzer | 341 |

| | | |
|-------------------|---|------------|
| 10.2.2 | Examining the Gimple Version of CFG | 342 |
| 10.2.3 | Examining the Result of Data Flow Analysis | 346 |
| 10.3 | Implementing the Generic Data Flow Analyzer <i>gdfa</i> | 352 |
| 10.3.1 | Specification Primitives | 352 |
| 10.3.2 | Interface with GCC | 354 |
| 10.3.3 | The Preparatory Pass | 358 |
| 10.3.4 | Local Data Flow Analysis | 358 |
| 10.3.5 | Global Data Flow Analysis | 360 |
| 10.4 | Extending the Generic Data Flow Analyzer <i>gdfa</i> | 363 |
| A | An Introduction to GCC | 365 |
| A.1 | About GCC | 365 |
| A.2 | Building GCC | 366 |
| A.3 | Further Readings in GCC | 368 |
| References | | 371 |
| Index | | 378 |