

1	Introduction to Some Programming Styles	1
1.1	Functional Programming	1
1.1.1	Easier Programming	2
1.1.2	Underlying Formalisms	3
1.1.3	Functions as Values	4
1.1.4	Constraints of Functional Programming	5
1.2	Generic Programming	7
1.2.1	Combining Type Flexibility and Type Precision	8
1.2.2	Combining Components Variability and Link Precision	10
1.3	Object Programming	12
1.3.1	Effective Modeling	13
1.3.2	Compatible Object Types	13
1.3.3	Objects as Values	14
1.4	Mixing Up Styles Together	14
2	Quick Introduction to OCaml	15
2.1	The Interactive Environment	15
2.1.1	Using the Interactive Environment	15
2.1.2	Typing	18
2.1.3	Exploiting the Standard Library	19
2.2	Type Reading	20
2.2.1	Verifying Existing Definitions	21
2.2.2	Reading Unary Function Types	21
2.2.3	Reading n-ary Function Types	22
2.2.4	Reading Parameterized Types	25
2.3	New Value Definitions	27
3	Elements of Functional Programming	31
3.1	Basics	31
3.1.1	Terminology	31
3.1.2	Variables and Bindings	33
3.1.3	Global Binding Definitions	33
3.1.4	Local Binding Definitions	36
3.1.5	Life and Hiding	37
3.1.6	Garbage-Collecting	39
3.1.7	Function Definitions	40
3.1.8	Recursive Function Definitions	41
3.1.9	Local Environments within Functions	42

3.1.10	Functional Values and Closures	45
3.1.11	The let's: a Partitioning System	47
3.2	Evaluation Strategies	48
3.2.1	Result Independance	48
3.2.2	Value Evaluation	49
3.2.3	Name and Lazy Evaluations	51
3.2.4	Choosing an Evaluation Strategy	54
3.2.5	Exceptions in Evaluation Strategies	55
4	Functions	57
4.1	Forms and Facets of Functions	57
4.1.1	Functional Parameters and Code Transmission	57
4.1.2	Functions in Data Structures and Code Organization	59
4.1.3	Anonymous Functions	60
4.1.4	Using Anonymous Functions	61
4.1.5	N-ary and Curried Functions	62
4.1.6	Using Curried Functions	63
4.1.7	Tail Recursive Functions	66
4.1.8	Infixation	69
4.2	Functional Genericity	71
4.2.1	Polymorphisms	71
4.2.2	Generic Functions	72
4.2.3	Generic Functions in Other Languages	75
4.2.4	Generic Predicates	77
4.2.5	The Limits of the Functional Genericity	78
4.3	Function Typing	80
4.3.1	Explicit Typing	80
4.3.2	Type Abbreviations	81
4.3.3	Using Explicit Typing	82
4.3.4	The Type Inference and its Error Messages	83
4.3.5	The Type Inference and the Search for Errors	85
5	Types	89
5.1	Type Zoology	89
5.1.1	The Classical Hierarchy	89
5.1.2	The Access Hierarchy	91
5.1.3	Types with Functional or Imperative Nature	93
5.2	Record Types	94
5.2.1	Defining Record Types	94
5.2.2	Instantiating Record Types	94
5.2.3	Accessing Fields	95
5.2.4	Record Type Possibilities	96

5.2.5	Data Types and Recursion with Record Types	97
5.2.6	The Limits and Advantages of Record Types	99
5.2.7	Type Redefinitions	100
5.3	Inductive Types	101
5.3.1	Inductive Type Definitions	101
5.3.2	Inductive Type Instanciations	102
5.3.3	Inductive Type Possibilities	103
5.3.4	The Inductivity of Inductive Types	105
5.4	Pattern Matching	106
5.4.1	Patterns	106
5.4.2	Pattern Matching at Work	106
5.4.3	Filtering	109
5.4.4	The Reasons of Using Filtering	112
5.4.5	The Limits of Pattern Matching and Filtering	114
5.5	Some Applications of Inductive Types	117
5.5.1	Unions of Distinct Types	117
5.5.2	Clarifying Code	118
5.5.3	Partial Functions	118
5.5.4	Emulated Overloading	119
5.5.5	Defensive Programming: Dense Typing Style	121
5.5.6	Simple Inductive Types and Record Types	123
5.5.7	Structured Expression Typing	124
5.5.8	Grammar Representations	125
5.6	The General Problem of Type Extensibility	129
5.6.1	Features and Criteria of Type Extensibility	129
5.6.2	Record Type Extensibility	130
5.6.3	Inductive Type Extensibility	131
5.6.4	The Inductive Types and the Explicit Labeled Types	133
5.6.5	Flexible Inductive Types: Polymorphic Variants	135
6	Functional Data Structures	141
6.1	Lists	142
6.1.1	A Sequential Data Structure Representation	142
6.1.2	Lists : A Predefined Structured Type	144
6.1.3	Some Functions on Lists	145
6.2	Programming Techniques on Functional Structures. I.	148
6.2.1	Iterators	148
6.2.2	Empty Structures and Partial Functions	149
6.2.3	Associative Tables and Structural Constraints	151
6.3	Trees	152
6.3.1	Binary Trees	152
6.3.2	Trees : an Example of Composed Data Structure	157

6.3.3 Multiple Compositions	160
6.4 Persistence	160
6.4.1 A Property of Functional Programming	160
6.4.2 The Advantages of Persistence	163
6.4.3 The Disadvantages of Persistence	165
6.5 Programming Techniques on Functional Structures. II.	166
6.5.1 Taming the Disadvantages of Persistence	166
6.5.2 Controlling Navigation within Data Structures	170
6.5.3 Tail Recursivity on Lists	173
6.5.4 Tail Recursivity on Trees	174
6.6 Functional Data Structures	176
6.6.1 The Limits of Inductive Types	176
6.6.2 Ambiguity and Inductive Types	178
6.6.3 Homogeneous and Heterogeneous Data Structures	183
6.6.4 Graphs and Non Functional Data Structures	186
7 Imperative Programming	193
7.1 Exceptions	194
7.1.1 Partial Functions and Error Handling	194
7.1.2 A Basic Type: the Exceptions	197
7.1.3 Raising Exceptions	197
7.1.4 Catching and Handling Exceptions	199
7.1.5 Exceptions as an Optimisation Tool	200
7.1.6 Exceptions as Values	202
7.2 Procedures and Unit	203
7.2.1 Procedures Are Not Functions	203
7.2.2 Sequences	205
7.2.3 A Simple if-then Construction	206
7.3 Using Procedures	206
7.3.1 Primitive Debugging Techniques	206
7.3.2 Batch Evaluations	207
7.3.3 Basic Graphics	209
7.3.4 Assertions	210
7.3.5 File Handling or OCaml as a Script Language	211
7.4 Arrays : A Predefined Type	214
7.4.1 Direct Access and Value Assignment	214
7.4.2 Obtaining New Arrays	215
7.4.3 Internal Iterators on Arrays	216
7.4.4 Loops	216
7.4.5 Strings: An Imperative Type	218
7.5 Records with Mutable Fields	219

7.6 References	219
7.6.1 Mutable Elements	219
7.6.2 References: A Basic Type	220
7.6.3 A Typing Problem: The Generic References	222
7.6.4 Imperative Operations and Generic References	223
7.6.5 Using Closures and Generic References	224
7.6.6 Imperative Data Structures and Generic References	224
7.6.7 Non-Generalization and Weak Type Variables	226
7.6.8 Non-Generalization and Function Applications	229
7.6.9 Imperative Data Structures and Weak Type Variables	231
7.7 Choosing to Use the Imperative Style	232
7.7.1 Several Problems of the Imperative Style	232
7.7.2 The Propagation of the Imperative Style	235
7.7.3 Interfacing OCaml with C	237
8 Functional Programming Techniques	239
8.1 Incremental Programming	240
8.1.1 An Example: Analyzing Symbol Sequences	241
8.1.2 A First Prototype	242
8.1.3 More Elaborated Tests	245
8.1.4 A Graphical Representation	248
8.1.5 The Advantages of Incremental Programming	249
8.2 Generalizations	251
8.2.1 The Idea of Generalization	251
8.2.2 Transformation Generalizations: Foldings	252
8.2.3 Summing up Generalizations	257
8.2.4 Algorithm Generalizations	258
8.2.5 Type Generalizations	263
8.2.6 Polytypism	265
8.2.7 Generalizations and Reuse	267
8.3 Data-Driven Programming	272
8.3.1 A Generalized Generalization	272
8.3.2 A Global Programming Technique	275
8.3.3 Imperative Data-Driven Programming	276
8.3.4 Type Extensibility and Data-Driven Programming	278
8.4 Functional Data Representations	279
8.4.1 Sets as Functions	280
8.4.2 Sub-Spaces as Functions	283
8.4.3 Graphic Objects as Functions	285
8.4.4 Real Numbers as Functions	288
8.5 Evaluation Control	289
8.5.1 Basics of Evaluation Control	290

8.5.2	Functional Freezing: A New Use of <code>unit</code>	290
8.5.3	Freezing and Lazyness	292
8.5.4	The Behavior of Functional Freezing	295
8.5.5	Data Structures with a Lazy Behavior	297
8.5.6	Freezing Evaluation Flow and Tail Recursivity	298
8.6	Lazy Lists or Streams	301
8.6.1	Freezing a Sequential Data Structure	301
8.6.2	Accessing the Elements of a Stream	303
8.6.3	Variations about Stream Definitions	304
8.6.4	Recursivity and Frozen Infinity	305
8.6.5	Iterators and Stream Compositions	307
8.6.6	Using Frozen Infinity	309
8.6.7	Streams and Lazyness Boundary	311
8.6.8	Generating Values by Streams	313
8.6.9	External Iterators as Streams	314
8.6.10	Infinite Sets as Streams	316
8.6.11	Streams: A Global Programming Technique	318
8.7	Lazy Trees	319
8.7.1	Freezing a Tree-like Structure	319
8.7.2	Using Lazy Trees	323
8.7.3	Choosing Explicit Lazyness	327
8.8	Continuation Passing Programming	328
8.8.1	Continuations	328
8.8.2	Continuations Passing and Partial Functions	329
8.8.3	Continuations Passing and Evaluation Control	331
8.8.4	Red-Black Trees	333
8.8.5	2-3 Trees	335
9	Modular Programming	341
9.1	Modules as a General Encapsulating Mean	342
9.1.1	Module Definitions	342
9.1.2	Accessing the Elements of a Module	343
9.1.3	Data Structures in a Modular Form	344
9.1.4	Remarks about Module Definitions	346
9.1.5	Local Modules	348
9.2	Signatures: Types for Modules	349
9.2.1	Inferred Signatures	349
9.2.2	Signatures Definitions	350
9.2.3	Abstract Data Types	351
9.2.4	Implemented Elements in Signatures	352
9.2.5	Signatures to Type Modules	353
9.2.6	Modules are Instances of Signatures	356

9.3 Signatures Writing Techniques	358
9.3.1 Signatures as Specification and Interface Means	358
9.3.2 The Limits of Signature Specifications	358
9.3.3 Overcoming the Limits of Signature Specifications	359
9.3.4 Signature Generalizations	360
9.3.5 Signatures for Functional and Imperative Styles	361
9.4 Public and Private Elements of Modules	362
9.4.1 Public Elements	362
9.4.2 Private Elements	363
9.4.3 Signature Compatibility	364
9.4.4 Public Exceptions	365
9.4.5 Public Types	366
9.4.6 Private Types and Abstract Data Types	367
9.5 Abstract Data Types	369
9.5.1 The Reasons of Information Hiding and Substitutivity	369
9.5.2 To Adapt Data Types	370
9.5.3 To Optimize Data Types by Memoization	372
9.5.4 Information Hiding and Generic Predefined Predicates	375
9.5.5 Information Hiding and Optimization by Imperative Features	376
9.5.6 "Public" Abstract Types	379
9.5.7 "Public" Abstract Types and Type Constraints	382
9.5.8 Conceptual Signature Generalizations	384
9.5.9 Naming Tactics for Abstract Data Types	386
9.5.10 Universal Type Parameters and Abstract Types	388
9.6 Module Linking by Inclusions	392
9.6.1 Module and Signature Inclusions	392
9.6.2 Inclusions and Inheritance	393
9.6.3 Inclusions and Adaptations	395
9.7 Module Linking by Sub-Components	396
9.7.1 Sub-Modules	396
9.7.2 Module Openings	397
9.7.3 Abstract Sub-Modules	399
9.7.4 Signature Linking by Abstract Sub-Modules	399
9.7.5 Abstract Sub-Modules and Constraints Inclusions	401
9.7.6 Hiding Types of Sub-Modules	402
9.7.7 Flattening Modular Levels	404
9.7.8 Modular Aggregates of Data Types	404
9.7.9 Modular Associations of Data Types	406
9.7.10A More Complete Example: The "Apple Men"	409
9.8 Information Hiding in Question	411
9.8.1 Choosing to Hide	411
9.8.2 The "Record-Modules"	413
9.8.3 The <i>a posteriori</i> Information Hiding	415
9.8.4 Information Hiding and Module Associations	416

9.8.5	The Limits of Type Constraints	417
9.8.6	The Extensibility of Value Representations	418
9.9	Modules as External Files and Batch Compilation	420
9.9.1	Loading Modules in the Interaction Loop	420
9.9.2	Module Batch Compilation	422
9.9.3	Compiled Modules and the Interaction Loop	424
9.9.4	Compiled Modules and Side-Effects	425
9.9.5	Super-Modules as Packages	426
10	Generic Modular Programming: Functors	431
10.1	Functors	432
10.1.1	The Idea of Module Functions	432
10.1.2	Functor Definitions	433
10.1.3	Using Functor Parameters	434
10.1.4	Applying Functors	435
10.1.5	Explicit Typing and Functors	436
10.1.6	Sharing Types and Type Transmission	437
10.1.7	Non-Modular Parameters	438
10.1.8	Functors : a Typed Generic Modular Programming	439
10.2	Functor Programming Techniques and Basic Design Patterns	440
10.2.1	Generic Modular Inheritance	440
10.2.2	Generic Modular Adaptations	442
10.2.3	Generic Modular Decorations	443
10.2.4	Generic Modular Composites	445
10.2.5	Generic Data Types	447
10.3	Functors and the Genericity Power	448
10.3.1	Signatures and Universal Type Parameters	448
10.3.2	Signatures and Abstract Types	449
10.3.3	Going from one Genericity to Another?	451
10.4	Functors and Batch Compilation	453
10.5	n-ary Functors	456
10.5.1	n-ary Functors Definitions	456
10.5.2	Applying n-ary Functors	457
10.5.3	A More Complete Example: Generic Graphs	461
10.5.4	Type Constraints over Functors Parameters	463
10.5.5	Sharing Types between Functors Parameters	467
10.5.6	A Problem: Sharing Types vs. Information Hiding	469
10.5.7	The "Data Type Nursery" Technique	470
10.6	Functor Signatures	472
10.6.1	Types for Functors	472
10.6.2	Specification and Functor Signatures	475

10.7	Functors of Functors: Higher-Order Functors	476
10.7.1	A First Example of Higher-Order Functors	476
10.7.2	Type Constraints over Functor Parameters	477
10.7.3	Tuning Genericity by Higher-Order Functors	477
10.7.4	Remarks about Functor Generalizations	480
10.7.5	Modules and Functors Are Almost First Class Citizen	481
10.8	Choosing Generic Modular Programming	482
10.8.1	Functors: Another Functional Programming	483
10.8.2	Functors: A Tool for Software Engineering	483
10.8.3	Generic Modular Programming in Question	487
10.9	A Generic Architecture Representation	489
10.9.1	Software Development and Generic Programming	489
10.9.2	Specification Graphs and Architecture Automata	491
10.9.3	Representing Signature Compatibilities	494
10.10	Examples of Architecture Automata	497
10.10.1	Generic Priority Queues	497
10.10.2	Signature Hierarchies Management	500
10.10.3	Generic Production Lines	501
10.10.4	Remarks about Architecture Automata	505
11	Object-Oriented Programming	507
11.1	Why Do One Need a New Kind of Values?	507
11.1.1	Objects as Records	508
11.1.2	Objects as Modules	509
11.1.3	Objects as Functions	511
11.2	Objects and Classes	513
11.2.1	Objects Definitions	513
11.2.2	Accessing Object Elements	515
11.2.3	The Object Self	516
11.2.4	Object Types	516
11.2.5	Object Type Compatibility	518
11.2.6	Open Types	520
11.2.7	Classes as Object Constructors	521
11.2.8	Open Types and Constraint Genericity	525
11.3	Some Class Mechanisms	525
11.3.1	Inheritance	525
11.3.2	Generic Classes	526
11.3.3	Constraint Generic Classes	529
11.3.4	Redefinitions and Dynamic Links	529
11.3.5	Class Types	531
11.3.6	Abstract Methods	533
11.4	Some Object Oriented Techniques	534

11.4.1	Object and Functional Programming	534
11.4.2	Using Object Type Compatibility	535
11.4.3	Typing n-ary Methods	540
11.4.4	Abstract Data Types as Classes	543
11.4.5	Object and Modular Programming	545
11.4.6	Object and Generic Modular Programming	546
11.5	Choosing Object Programming	550
11.5.1	The Main Advantages of Object Oriented Programming	550
11.5.2	Object Oriented Programming and Recursive Components	550
11.5.3	The Extensibility and Object Oriented Programming	552
11.5.4	The Main Drawbacks of Object Oriented Programming	553