

Table of Contents

| | |
|--|-------------|
| About the Author | xv |
| About the Technical Reviewer | xvii |
| Acknowledgments | xix |
| Introduction | xxi |
| Part I: Definition..... | 1 |
| Chapter 1: Why Immutable Architecture | 3 |
| The Immutability Solution | 3 |
| The Problems with Immutability | 4 |
| Begin a New Journey..... | 4 |
| The Fallacies of Distributed Computing | 5 |
| The Network Is Not Reliable | 6 |
| Latency Is Not Zero..... | 6 |
| Topology Doesn't Change | 7 |
| Changing Assumptions | 8 |
| Immutability Changes Everything | 9 |
| Shared Mutable State..... | 9 |
| Structural Sharing | 10 |
| The Two Generals' Problem..... | 12 |
| A Prearranged Protocol | 14 |
| Reducing the Uncertainty | 15 |
| An Additional Message | 16 |
| Proof of Impossibility..... | 17 |
| Relaxing Constraints | 18 |
| Redefining the Problem | 19 |
| Decide and Act..... | 20 |

TABLE OF CONTENTS

| | |
|---|-----------|
| Accept the Truth | 20 |
| A Valid Protocol..... | 21 |
| Examples of Immutable Architectures | 22 |
| Git | 23 |
| Blockchain | 24 |
| Docker | 26 |
| Chapter 2: Forms of Immutable Architecture | 29 |
| Deriving State from History..... | 29 |
| Historical Records | 30 |
| Mutable Objects..... | 31 |
| Projections..... | 33 |
| Event Sourcing | 35 |
| Generating Events | 35 |
| CQRS..... | 36 |
| DDD | 37 |
| Taking a Functional View | 39 |
| Commutative and Idempotent Events..... | 40 |
| Asynchronous Model View Update..... | 40 |
| The Update Loop..... | 41 |
| Unidirectional Data Flow | 43 |
| Immutable App Architecture | 44 |
| Historical Modeling | 45 |
| Partial Order | 46 |
| Predecessors..... | 47 |
| Successors | 48 |
| Immutable Graphs | 50 |
| Collaboration | 51 |
| Acyclic Graphs | 52 |
| Timeliness | 53 |

TABLE OF CONTENTS

| | |
|--|-----------|
| Limitations of Historical Modeling | 54 |
| No Central Authority | 54 |
| No Real-Time Clock | 55 |
| No Uniqueness Constraints | 56 |
| No Aggregation | 57 |
| Chapter 3: How to Read a Historical Model | 59 |
| Fact Type Graphs..... | 60 |
| A Chess Game | 64 |
| Important Attributes..... | 65 |
| A Chain of Facts..... | 66 |
| Endgame | 68 |
| Fact Instance Graphs | 71 |
| The Immortal Game..... | 74 |
| Collecting Moves | 75 |
| A Brilliant Win | 77 |
| The Factual Modeling Language | 79 |
| Declaring Fact Types | 79 |
| Querying the Model | 81 |
| Jumping Levels | 82 |
| Joining Matches | 83 |
| Existential Quantifiers..... | 84 |
| Current Value | 86 |
| Authorization Rules | 87 |
| A Chess Application | 88 |
| Use Cases | 89 |
| User Interface | 90 |

TABLE OF CONTENTS

| | |
|---|-----------|
| Part II: Application..... | 93 |
| Chapter 4: Location Independence | 95 |
| Modeling with Immutability | 96 |
| Synchronization | 96 |
| Exploring Contracts..... | 97 |
| Identity | 97 |
| Auto-incremented IDs..... | 97 |
| URLs | 101 |
| Location-Independent Identity..... | 102 |
| Causality | 107 |
| Putting Steps in Order | 107 |
| The Transitive Property..... | 108 |
| Concurrency | 110 |
| Partial Order | 111 |
| The CAP Theorem..... | 112 |
| Defining CAP..... | 112 |
| Proving the CAP Theorem | 114 |
| Eventual Consistency | 117 |
| Kinds of Consistency | 118 |
| Strong Eventual Consistency in a Relay-Based System | 119 |
| Idempotence and Commutativity..... | 120 |
| Deriving Strong Eventual Consistency..... | 122 |
| The Contact Management System..... | 124 |
| Replaying History | 127 |
| Conflict-Free Replicated Data Types (CRDTs)..... | 128 |
| State-Based CRDTs | 128 |
| Vector Clocks..... | 131 |

TABLE OF CONTENTS

| | |
|--|------------|
| A History of Facts..... | 134 |
| Sets | 134 |
| Historical Records | 136 |
| Historical Facts..... | 143 |
| Conclusion | 143 |
| Chapter 5: Analysis..... | 145 |
| Use Cases | 146 |
| From Use Case to Decision..... | 147 |
| From Extension to Succession | 148 |
| Data..... | 151 |
| Identifiers | 151 |
| Cardinality | 152 |
| Mutation | 155 |
| Views | 158 |
| Finding a Place to Start | 158 |
| Annotated Wireframes..... | 159 |
| Removal from Lists..... | 160 |
| Collaboration..... | 164 |
| Regions..... | 165 |
| Crossing Boundaries..... | 167 |
| Conversations..... | 168 |
| Valid Orderings..... | 170 |
| Eliminating Race Conditions..... | 171 |
| Responding to Different Valid Orderings..... | 172 |
| Consequences..... | 175 |
| Indexes | 175 |
| Expected Number of Results | 178 |
| No Implicit Order | 180 |

TABLE OF CONTENTS

| | |
|---|------------|
| Chapter 6: State Transitions | 183 |
| Many Properties..... | 184 |
| Shipping and Billing..... | 185 |
| Introducing Back-Orders | 186 |
| Cancellations and Returns..... | 187 |
| Parallel State Machines..... | 188 |
| Many Children | 189 |
| Software Issue Tracking | 189 |
| Child State | 190 |
| Composite State Transition Diagrams..... | 191 |
| A Declarative Function of States | 191 |
| Conditional Validation..... | 193 |
| Nullability Based on State | 193 |
| Cycles in State Transition | 195 |
| Collect Data During Transitions | 195 |
| Immutable State Transitions..... | 197 |
| The Question Behind State..... | 198 |
| Translating a State Machine to a Historical Model | 198 |
| Reasons for Computing State..... | 204 |
| Single Source of Truth..... | 208 |
| Orchestrators..... | 208 |
| Convergent Histories | 210 |
| Chapter 7: Security | 213 |
| Proof of Authorship | 214 |
| Key Pairs..... | 214 |
| Digest | 215 |
| Authorization..... | 217 |
| Principal Facts..... | 218 |
| Authorization Query..... | 218 |
| Initial Authorization..... | 220 |

TABLE OF CONTENTS

| | |
|--|------------|
| Grant of Authority | 221 |
| Limited Authority | 222 |
| Indefinite Authorization..... | 223 |
| Transitive Authorization | 225 |
| Revocation..... | 226 |
| Authorization Upon Receipt | 228 |
| Confidentiality | 229 |
| Untrusted Nodes..... | 229 |
| Asymmetric Encryption | 230 |
| Encrypting Historical Facts..... | 232 |
| Limit the Distribution of Confidential Facts | 232 |
| Attacks and Countermeasures | 235 |
| Secrecy | 236 |
| Shared Symmetric Key | 237 |
| Limit the Scope of a Shared Key | 240 |
| Chapter 8: Patterns..... | 243 |
| Structural Patterns..... | 243 |
| Entity | 244 |
| Ownership | 246 |
| Delete | 250 |
| Restore | 252 |
| Membership | 255 |
| Mutable Property | 258 |
| Entity Reference | 265 |
| Workflow Patterns..... | 268 |
| Transaction | 269 |
| Queue | 272 |
| Period | 275 |
| Outbox | 279 |
| Designing from Constraints | 286 |

TABLE OF CONTENTS

| | |
|--|------------|
| Part III: Implementation..... | 287 |
| Chapter 9: Query Inverses | 289 |
| Mechanizing the Problem | 290 |
| The Anatomy of a Query..... | 291 |
| A Sequence of Steps | 292 |
| Filter by Existential Condition | 292 |
| The Affected Set..... | 294 |
| Computing the Affected Set..... | 295 |
| Inverting Longer Queries | 296 |
| Unsatisfiable Inverses | 297 |
| Walking Backward | 298 |
| Proof of Completeness | 299 |
| New Results..... | 300 |
| Forward Optimization | 301 |
| Existential Conditions..... | 302 |
| Recursive Inversion | 303 |
| Tail Conditions | 304 |
| Removing Results..... | 306 |
| When Removal Isn't Removal | 307 |
| Nested Subqueries..... | 309 |
| Tautological Conditions..... | 310 |
| Proof of Completeness Continued | 313 |
| Potential vs. Actual Change | 314 |
| Removing Absent Results | 315 |
| Caches Are Sets..... | 316 |
| Query Inversion in Practice..... | 316 |
| Chapter 10: SQL Databases | 319 |
| Identity | 320 |
| Content-Addressed Storage | 320 |
| Table Structure | 325 |

TABLE OF CONTENTS

| | |
|--|------------|
| Relationships | 326 |
| Inserting Successors | 327 |
| Optional Predecessors..... | 328 |
| Many Predecessors | 328 |
| Queries..... | 332 |
| Joins | 333 |
| Correlated Subqueries..... | 333 |
| Derived Tables | 334 |
| Selecting Results..... | 336 |
| Optimization..... | 337 |
| Spurious Joins..... | 338 |
| Covering Indexes | 339 |
| Where Not Exists | 340 |
| Integration..... | 344 |
| Legacy Application Integration | 344 |
| Reporting Databases | 347 |
| Application-Agnostic Stores..... | 348 |
| A Generic Fact Table..... | 349 |
| Predecessor Relationships | 350 |
| Versioning..... | 352 |
| Chapter 11: Communication | 355 |
| Delivery Guarantees..... | 356 |
| Best Effort..... | 357 |
| Confirmation | 357 |
| Durable Protocols | 362 |
| Message Processing | 364 |
| Most Protocols Are Asynchronous | 364 |
| HTTP Is Usually Synchronous | 364 |

TABLE OF CONTENTS

| | |
|---|------------|
| Data Synchronization | 365 |
| Within an Organization | 366 |
| Between Organizations..... | 371 |
| Occasionally Connected Clients | 375 |
| Chapter 12: Generated Behaviors..... | 385 |
| Projections | 386 |
| Defining Projections | 386 |
| Projection Pipelines..... | 388 |
| Interest..... | 389 |
| Interest in Deleted Entities | 391 |
| Interest in Past Periods | 392 |
| Sharing Interest..... | 393 |
| Losing Interest..... | 394 |
| Immutable Runtimes..... | 396 |
| Model Generation | 397 |
| Query Execution | 397 |
| Testing | 398 |
| User Interaction | 399 |
| Collaboration | 400 |
| Immutable Organizations..... | 402 |
| Decision Substrate | 403 |
| Globally Distributed Systems..... | 403 |
| Index..... | 405 |