

Table of Contents

- 1 Introduction 1**
 - 1.1 Motivation 1
 - 1.2 State of the Practice and State of the Art 2
 - 1.3 Research Goals and Contributions..... 3
 - 1.4 Research Method 5
 - 1.5 Outline 5
- 2 Background 9**
 - 2.1 Domain Driven Design 9
 - 2.2 Consistency and Concurrency 11
 - 2.2.1 ACID Transaction Guarantees..... 11
 - 2.2.2 Global Transactions for Distributed Systems 15
 - 2.2.3 Transactional Replication 16
 - 2.2.4 Non-Transactional Distributed Systems 18
 - 2.2.5 Paradigm Shift towards the Application Layer 22
 - 2.3 Chapter Summary 27
- 3 Related Work..... 29**
 - 3.1 Software Engineering Guidance..... 29
 - 3.1.1 Saga Patterns 31
 - 3.1.2 DDD Aggregates 32
 - 3.1.3 Event Sourcing 33
 - 3.1.4 Command Query Responsibility Segregation 34
 - 3.1.5 Transactional Outbox Pattern 35
 - 3.1.6 Change Data Capture 36
 - 3.2 Empirical Studies..... 36
 - 3.3 Chapter Summary 38
- 4 Problem and Research Method 39**
 - 4.1 Initial Theory based on Anecdotal Observations 39
 - 4.1.1 Anecdotal Observations on Transaction Isolation Levels 40
 - 4.1.2 Cases 41

4.2	Research Method	42
5	ECD3 – Architecting Safe Eventually Consistent Systems...	47
5.1	Goals	47
5.2	Domain Operations Design Guide	48
5.3	Domain Objects Design Guide	49
5.4	Prerequisites and Guarantees of ECD3-compliant Programming Frameworks	50
5.4.1	Programming Model	50
5.4.2	Transactions and Update Propagation	51
5.4.3	Reconciliation	52
5.5	Chapter Summary	53
6	ECD3 – Domain Objects Design Guide	55
6.1	Definitions	55
6.2	Taxonomy	57
6.2.1	Trivial Aggregates	58
6.2.2	Non-Trivial Aggregates	64
6.2.3	Taxonomy Cheat Sheet	68
6.3	Best Practices	68
6.3.1	Trivial Aggregates First	68
6.3.2	Non-Trivial Aggregates? – Make Well-Informed Trade-Off Decisions	69
6.4	Design Patterns	70
6.4.1	The Derived Monotonic State Pattern	70
6.4.2	The Segregate Aggregate Classes Pattern	76
6.5	Chapter Summary	82
7	ECD3 – Domain Operations Design Guide	83
7.1	Basic Design Goals	83
7.1.1	Tolerance to Partial Execution Order	83
7.1.2	Aggregate Consistency	85
7.2	Compatibility Relation	85
7.2.1	Best Practices	86
7.3	Antipatterns	89
7.3.1	State-based Update Propagation in Disguise	89
7.3.2	Implementing Incremental Updates as Blind Updates	91
7.4	Cheat Sheet	93

7.5	Chapter Summary	94
8	ECD3 – Reconciliation	97
8.1	A Notion of Concurrency in Eventually Consistent Systems	97
8.1.1	Common Concurrency Anomalies	100
8.1.2	Summary	104
8.2	ECD3 Reconciliation Process	104
8.2.1	ECD3 Transaction Management	105
8.2.2	ECD3 Reconciliation Algorithm.....	112
8.3	Reconciliation Semantics	115
8.3.1	Healing of Distributed Lost Updates.....	115
8.3.2	Healing of Distributed Write Skews.....	117
8.3.3	Healing of Incorrect Program Flow.....	118
8.3.4	Summary	119
8.4	Reconciliation Guarantees	120
8.5	Limitations	121
8.6	Required Guarantees of the Infrastructure.....	121
8.7	Chapter Summary and Implications.....	122
9	ECD3 – Programming Framework	125
9.1	Usage Context.....	125
9.2	Architecture Drivers.....	126
9.3	Prerequisites & Constraints.....	127
9.4	Major Technology Decisions	127
9.5	Major Building Blocks	128
9.6	Programming Model.....	129
9.6.1	Getting Started	130
9.6.2	Basic Configuration	131
9.6.3	Implementing Aggregates	133
9.6.4	Implementing Repositories.....	133
9.6.5	Implementing Transactions	133
9.7	Source Code.....	136
9.8	Limitations	136
9.8.1	Persistence.....	136
9.8.2	Recovery.....	137
9.8.3	Multiversion Repository Cache	138
9.8.4	Pessimistic Commit Operation.....	138
9.8.5	Sealing.....	138

9.8.6	Programming Model	138
9.9	Chapter Summary	139
10	Validation	141
10.1	Validation Approach	141
10.2	Hypotheses	142
10.3	Action Research Study	148
10.3.1	Research Design	149
10.3.2	Context	149
10.3.3	Theoretical Framework	150
10.3.4	Summary of Research Cycles	151
10.3.5	Data Collection and Analysis Methods	154
10.3.6	Results and Interpretation	157
10.3.7	Validity	162
10.3.8	Summary & Conclusions	163
10.4	Informal Validation with External Practitioners	163
10.4.1	Goals	164
10.4.2	Implementation	164
10.4.3	Limitations	168
10.4.4	Lessons Learned	169
10.4.5	Summary & Conclusions	170
10.5	ECD3 Design Workshop Surveys	171
10.5.1	Goals	171
10.5.2	Workshop Concept	171
10.5.3	Survey Design	172
10.5.4	Survey Implementation	175
10.5.5	Survey Results	177
10.5.6	Limitations	182
10.5.7	Summary & Conclusions	183
10.6	ECD3 Framework Experiments	184
10.6.1	Goals	185
10.6.2	Experiment Design	185
10.6.3	Experiment Implementation	191
10.6.4	Experiment Results	192
10.6.5	Discussion	199
10.6.6	Implications	204
10.6.7	Limitations	205
10.6.8	Summary & Conclusions	205

10.7 Chapter Summary	207
11 Conclusions	211
11.1 Contributions	211
11.2 Limitations	213
11.3 Implications	215
11.4 Future Research Agenda	217
11.5 Concluding Remarks	217
References	219
A Appendix: Workshop Survey Questionnaire.....	227