## Contents

## Part I An Inflection Point for Enterprise Applications

1	Desir	ability,	Feasibility, Viability: The Impact of In-Memory	3		
	1.1	Inform	ation in Real Time: Anything, Anytime, Anywhere	3		
		1.1.1	Response Time at the Speed of Thought	4		
		1.1.2	Real-Time Analytics and Computation on the Fly	6		
	1.2	The In	npact of Recent Hardware Trends	6		
		1.2.1	Database Management Systems for			
			Enterprise Applications	7		
		1.2.2	Main Memory is the New Disk	10		
		1.2.3	From Maximizing CPU Speed			
			to Multi-Core Processors.	11		
		1.2.4	Increased Bandwidth Between CPU			
			and Main Memory	13		
	1.3	Reduci	ing Cost Through In-Memory Data Management	16		
		1.3.1	Total Cost of Ownership.	16		
		1.3.2	Cost Factors in Enterprise Systems	17		
		1.3.3	In-Memory Performance Boosts Cost Reduction	18		
	1.4	Conclu	sion	19		
2	Why	Are En	terprise Applications So Diverse?	21		
	2.1	Current Enterprise Applications				
	2.2	Examples of Enterprise Applications				
	2.3	Enterprise Application Architecture				
	2.4	Data Processing in Enterprise Applications				
	2.5	Data Access Patterns in Enterprise Applications 2				
	2.6	Conclu	usion	27		

xxiii

ĒK

3.1 Targeting Multi-Core and Main Memory 30   3.2 Designing an In-Memory Database System 3   3.3 Organizing and Accessing Data in SanssouciDB 3   3.4 Conclusion 3   9 Part II SanssouciDB: A Single Source of Truth Through In-Memory   4 The Technical Foundations of SanssouciDB 39   4.1 Understanding Memory Hierarchies 40   4.1.2 Organization of the Memory Hierarchy 44   4.1.3 Trends in Memory Hierarchies 44   4.1.4 Memory from a Programmer's Point of View 44   4.1.4 Memory from a Programmer's Point of View 44   4.2 Parallel Data Processing Using Multi-Core 54   4.2.1 Increasing Capacity by Adding Resources 56   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.2.4 Parallel Dat
3.2 Designing an In-Memory Database System 3   3.3 Organizing and Accessing Data in SanssouciDB 3   3.4 Conclusion 3   9art II SanssouciDB: A Single Source of Truth Through In-Memory   4 The Technical Foundations of SanssouciDB 3   4.1 Understanding Memory Hierarchies 4   4.1.1 Introduction to Main Memory 4   4.1.2 Organization of the Memory Hierarchies 4   4.1.3 Trends in Memory Hierarchies 4   4.1.4 Memory from a Programmer's Point of View 4   4.2 Parallel Data Processing Using Multi-Core 5   4.2.1 Increasing Capacity by Adding Resources 5   4.2.2 Parallel System Architectures 5   4.2.3 Parallel Ization in Databases for Enterprise 5   4.2.4 Parallel Data Processing in SanssouciDB 6   4.3 Compression for Speed and Memory Consumption 6   4.3 Light-Weight Compression 6
3.3 Organizing and Accessing Data in SanssouciDB 3:   3.4 Conclusion 3:   9art II SanssouciDB: A Single Source of Truth Through In-Memory   4 The Technical Foundations of SanssouciDB 36   4.1 Understanding Memory Hierarchies 46   4.1.1 Introduction to Main Memory 46   4.1.2 Organization of the Memory Hierarchies 47   4.1.3 Trends in Memory Hierarchies 47   4.1.4 Memory from a Programmer's Point of View 46   4.2 Parallel Data Processing Using Multi-Core 57   4.2.1 Increasing Capacity by Adding Resources 56   4.2.2 Parallel System Architectures 56   4.2.3 Parallel Ization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3 Light-Weight Compression 67   4.3.1 Light-Weight Compression 67
3.4 Conclusion 3:   Part II SanssouciDB: A Single Source of Truth Through In-Memory   4 The Technical Foundations of SanssouciDB 3:   4.1 Understanding Memory Hierarchies 4:   4.1 Introduction to Main Memory 4:   4.1.1 Introduction to Main Memory Hierarchies 4:   4.1.2 Organization of the Memory Hierarchies 4:   4.1.3 Trends in Memory Hierarchies 4:   4.1.4 Memory from a Programmer's Point of View 4:   4.2 Parallel Data Processing Using Multi-Core 5:   4.2.1 Increasing Capacity by Adding Resources 5:   4.2.2 Parallel System Architectures 5:   4.2.3 Parallelization in Databases for Enterprise 5:   4.2.4 Parallel Data Processing in SanssouciDB 5:   4.3 Compression for Speed and Memory Consumption 6:   4.3 Light-Weight Compression 6:
Part II SanssouciDB: A Single Source of Truth Through In-Memory   4 The Technical Foundations of SanssouciDB 39   4.1 Understanding Memory Hierarchies 40   4.1.1 Introduction to Main Memory 40   4.1.2 Organization of the Memory Hierarchy 44   4.1.3 Trends in Memory Hierarchies 44   4.1.4 Memory from a Programmer's Point of View 40   4.2 Parallel Data Processing Using Multi-Core 50   4.2.1 Increasing Capacity by Adding Resources 50   4.2.2 Parallel System Architectures 50   4.2.3 Parallelization in Databases for Enterprise 50   4.2.4 Parallel Data Processing in SanssouciDB 60   4.3 Compression for Speed and Memory Consumption 64   4.3.1 Light-Weight Compression 65
4 The Technical Foundations of SanssouciDB 39   4.1 Understanding Memory Hierarchies 40   4.1.1 Introduction to Main Memory 44   4.1.2 Organization of the Memory Hierarchy 44   4.1.3 Trends in Memory Hierarchies 44   4.1.4 Memory from a Programmer's Point of View 46   4.2 Parallel Data Processing Using Multi-Core 56   4.2.1 Increasing Capacity by Adding Resources 56   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3 Light-Weight Compression 66
4.1 Understanding Memory Hierarchies 44   4.1.1 Introduction to Main Memory 44   4.1.2 Organization of the Memory Hierarchy. 44   4.1.3 Trends in Memory Hierarchies 44   4.1.4 Memory from a Programmer's Point of View 44   4.2 Parallel Data Processing Using Multi-Core 44   4.2.1 Increasing Capacity by Adding Resources 54   4.2.2 Parallel System Architectures 56   4.2.3 Parallel Data Processing in SanssouciDB 56   4.2.4 Parallel Data Processing in SanssouciDB 66   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.1.1 Introduction to Main Memory 44   4.1.2 Organization of the Memory Hierarchy 44   4.1.3 Trends in Memory Hierarchies 44   4.1.3 Trends in Memory Hierarchies 44   4.1.4 Memory from a Programmer's Point of View 46   4.2 Parallel Data Processing Using Multi-Core 46   4.2.1 Increasing Capacity by Adding Resources 56   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.1.2 Organization of the Memory Hierarchy. 44   4.1.3 Trends in Memory Hierarchies 44   4.1.4 Memory from a Programmer's Point of View 44   4.2 Parallel Data Processing Using Multi-Core 44   4.2 Parallel Data Processing Using Multi-Core 55   4.2.1 Increasing Capacity by Adding Resources. 56   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.1.3 Trends in Memory Hierarchies 4:   4.1.4 Memory from a Programmer's Point of View 4:   4.2 Parallel Data Processing Using Multi-Core 4:   4.2 Parallel Data Processing Using Multi-Core 5:   4.2.1 Increasing Capacity by Adding Resources 5:   4.2.2 Parallel System Architectures 5:   4.2.3 Parallelization in Databases for Enterprise 5:   4.2.4 Parallel Data Processing in SanssouciDB 5:   4.3.1 Light-Weight Compression 6:
4.1.4 Memory from a Programmer's Point of View 44   4.2 Parallel Data Processing Using Multi-Core and Across Servers. 57   4.2.1 Increasing Capacity by Adding Resources. 56   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise Applications 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.2 Parallel Data Processing Using Multi-Core   and Across Servers. 5:   4.2.1 Increasing Capacity by Adding Resources. 5:   4.2.2 Parallel System Architectures 5:   4.2.3 Parallelization in Databases for Enterprise 5:   4.2.4 Parallel Data Processing in SanssouciDB 5:   4.3 Compression for Speed and Memory Consumption 6:   4.3.1 Light-Weight Compression 6:
and Across Servers. 57   4.2.1 Increasing Capacity by Adding Resources. 54   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.2.1 Increasing Capacity by Adding Resources. 54   4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.2.2 Parallel System Architectures 56   4.2.3 Parallelization in Databases for Enterprise 56   4.2.4 Parallel Data Processing in SanssouciDB 56   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
4.2.3 Parallelization in Databases for Enterprise   Applications 54   4.2.4 Parallel Data Processing in SanssouciDB 66   4.3 Compression for Speed and Memory Consumption 66   4.3.1 Light-Weight Compression 66
Applications 51   4.2.4 Parallel Data Processing in SanssouciDB 60   4.3 Compression for Speed and Memory Consumption 64   4.3.1 Light-Weight Compression 65
4.2.4 Parallel Data Processing in SanssouciDB 60   4.3 Compression for Speed and Memory Consumption 64   4.3.1 Light-Weight Compression 65   4.3.2 Harry Weight Compression 65
4.3 Compression for Speed and Memory Consumption 64   4.3.1 Light-Weight Compression 64   4.3.2 Hight-Weight Compression 64
4.3.1 Light-Weight Compression
4.2.2 Henry Weight Commence
4.3.2 Heavy-weight Compression
4.3.3 Data-Dependent Optimization
4.3.4 Compression-Aware Ouery Execution
4.3.5 Compression Analysis on Real Data
4.4 Column, Row, Hybrid: Optimizing the Data Layout
4.4.1 Vertical Partitioning
4.4.2 Finding the Best Layout
4.4.3 Challenges for Hybrid Databases
4.4.4 Application Scenarios
4.5 The Impact of Virtualization 7
4.5.1 Virtualizing Analytical Workloads
4.5.2 Data Model and Benchmarking Environment
453 Virtual Versus Native Execution 8
454 Response Time Degradation with Concurrent VMs 8'
46 Summarizing the Technical Concents

5	Orga	nizing a	nd Accessing Data in SanssouciDB	97	
	5.1	SQL fo	r Accessing In-Memory Data	98	
		5.1.1	The Role of SQL	98	
		5.1.2	The Lifecycle of a Query	99	
		5.1.3	Stored Procedures	99	
		5.1.4	Data Organization and Indices	100	
		5.1.5	Any Attributes as Index	101	
	5.2	Increase	ing Performance with Data Aging	103	
		5.2.1	Active and Passive Data	104	
		5.2.2	Implementation Considerations for an		
			Aging Process	105	
		5.2.3	The Use Case for Horizontal Partitioning of Leads	106	
	5.3	Efficier	nt Retrieval of Business Objects	108	
		5.3.1	Retrieving Business Data from a Database	109	
		5.3.2	Object Data Guide	109	
	5.4	Efficier	nt Execution of Business Functions	111	
		5.4.1	Separating Business Functions from		
			Application Functions	111	
		5.4.2	Comparing Business Functions	112	
	5.5	Handlir	ng Data Changes in Read-Optimized Databases	114	
		5.5.1	The Impact on SanssouciDB	115	
		5.5.2	The Merge Process.	116	
		5.5.3	Improving Performance with Single Column Merge	120	
	5.6	Append	d, Never Delete, to Keep the History Complete	123	
		5.6.1	Insert-Only Implementation Strategies	123	
		5.6.2	Minimizing Locking Through Insert-Only	125	
		5.6.3	The Impact on Enterprise Applications	128	
		5.6.4	Feasibility of the Insert-Only Approach	130	
	5.7	5.7 Enabling Analytics on Transactional Data			
		5.7.1	Aggregation on the Fly	133	
		5.7.2	Analytical Queries without a Star Schema.	142	
	5.8 Extending Data Layout Without Downtime				
		5.8.1	Reorganization in a Row Store	149	
		5.8.2	On-The-Fly Addition in a Column Store	150	
	5.9	Busines	ss Resilience Through Advanced Logging		
		Technie	ques	151	
		5.9.1	Recovery in Column Stores.	152	
		5.9.2	Differential Logging for Row-Oriented Databases	154	
		5.9.3	Providing High Availability	155	
	5.10	The Im	portance of Optimal Scheduling		
		xed Workloads	156		
		5.10.1	Introduction to Scheduling	156	
		5.10.2	Characteristics of a Mixed Workload	159	

S

	5.10.3	Scheduling Short and Long Running Tasks	160
5.11	Conclu	sion	163

## Part III How In-Memory Changes the Game

6	Appl	ication I	Development	167		
	6.1	Optimizing Application Development for SanssouciDB				
		6.1.1	An In-Memory Application Programming Model	168		
		6.1.2	Application Architecture	172		
		6.1.3	Moving Business Logic into the Database	173		
		6.1.4	Best Practices	175		
		6.1.5	Graphical Creation of Views	176		
	6.2	tive Enterprise Applications	178			
		6.2.1	New Analytical Applications	179		
		6.2.2	Operational Processing to Simplify Daily Business	182		
		6.2.3	Information at Your Fingertips with Innovative			
			User-Interfaces.	185		
		6.2.4	Combining Analytics and Textsearch	190		
		6.2.5	Basic Types of Search	191		
		6.2.6	Features for Enterprise Search	191		
	6.3	Conclu	usion	194		
7	Finally, A Real Business Intelligence System is at Hand					
	7.1 Analytics on Operational Data					
		7.1.1	Yesterday's Business Intelligence.	196		
		7.1.2	Today's Business Intelligence	199		
		7.1.3	Drawbacks of Separating Analytics			
			from Daily Operations	201		
		7.1.4	Dedicated Database Designs for Analytical Systems	202		
		7.1.5	Analytics and Query Languages.	205		
		7.1.6	Enablers for Changing Business Intelligence	206		
		7.1.7	Tomorrow's Business Intelligence	208		
	7.2	How to	o Evaluate Databases After the Game has Changed	209		
		7.2.1	Benchmarks in Enterprise Computing	210		
		7.2.2	Changed Benchmark Requirements			
			for a Mixed Workload	211		
		7.2.3	A New Benchmark for Daily Operations			
			and Analytics	213		
	7.3	Conclusion				
8	Scali	ing Sans	souciDB in the Cloud	219		
	8.1	What 1	Is Cloud Computing?	220		
	8.2	Types of Cloud Applications 22				

## Contents

.

	8.3	Cloud Com	puting from	the Prov	ider Pers	pective.			. 223
		8.3.1 Mu	lti-Tenancy.						. 223
		8.3.2 Lov	w-End Versu	s High-I	End Hard	lware			. 228
		8.3.3 Rep	olication						. 229
		8.3.4 Ene	ergy Efficien	cy by Er	mploying	ç			
		In-I	Memory Tec	hnology		· · · · · · ·			. 230
	8.4	Conclusion							. 231
9	In-M	emory Revo	lution has B	egun .					. 233
	9.1	Risk-Free T	'ransition to	In-Memo	ory Data	Managen	nent		. 233
		9.1.1 Op	erating In-M	emory a	nd Tradi	tional			
		Sys	tems Side b	Side .					. 234
		9.1.2 Sys	stem Consoli	dation a	nd Exten	sibility .			. 235
	9.2 Customer Proof Points								. 236
		9.2.1 Cha	arité—Unive	rsitätsme	edizin Be	rlin			. 237
		9.2.2 Hil	ti						. 239
	9.3	Conclusion		••••				• • • •	. 241
Ał	oout th	e Authors		••••		••••			. 243
GI	ossary			••••					. 245
Re	eferenc	es							. 255
In	dex								. 263