# Table of Contents for All Volumes

## **VOLUME I Foundations and Vanilla Models**

Pa	rt I I	oundations	
1	$\operatorname{Intr}$	oduction to Arbitrage Pricing Theory	3
	1.1	The Setup	3
	1.2	Trading Gains and Arbitrage	7
	1.3	Equivalent Martingale Measures and Arbitrage	8
	1.4	Derivative Security Pricing and Complete Markets	10
	1.5	Girsanov's Theorem	12
	1.6	Stochastic Differential Equations	14
	1.7	Explicit Trading Strategies and PDEs	16
	1.8	Kolmogorov's Equations and the Feynman-Kac Theorem .	18
	1.9	Black-Scholes and Extensions	21
		1.9.1 Basics	21
		1.9.2 Alternative Derivation	25
		1.9.3 Extensions	27
		1.9.3.1 Deterministic Parameters and Dividends	27
		1.9.3.2 Stochastic Interest Rates	28
	1.10	Options with Early Exercise Rights	30
		1.10.1 The Markovian Case	29

XII	Contents

		1.10.2	Some General Bounds
		1.10.3	Early Exercise Premia
<b>2</b>	Fini	to Diff	erence Methods
4	2.1		ensional PDEs: Problem Formulation
	$\frac{2.1}{2.2}$		Difference Discretization
	2.2	2.2.1	Discretization in x-Direction. Dirichlet Boundary
		2.2.1	Conditions
		2.2.2	Other Boundary Conditions
		2.2.3	Time-Discretization
		2.2.4	Finite Difference Scheme
	2.3		ty
		2.3.1	Matrix Methods
		2.3.2	Von Neumann Analysis
	2.4		quidistant Discretization
	2.5		hing and Continuity Correction
		2.5.1	Crank-Nicolson Oscillation Remedies
		2.5.2	Continuity Correction
		2.5.3	Grid Shifting
	2.6	Conve	etion-Dominated PDEs
		2.6.1	Upwinding
		2.6.2	Other Techniques
	2.7	Option	Examples
		2.7.1	Continuous Barrier Options
		2.7.2	Discrete Barrier Options
		2.7.3	Coupon-Paying Securities and Dividends
		2.7.4	Securities with Early Exercise
		2.7.5	Path-Dependent Options
		2.7.6	Multiple Exercise Rights
	2.8		I Issues
		2.8.1	Mesh Refinements for Multiple Events
		2.8.2	Analytics at the Last Time Step
		2.8.3	Analytics at the First Time Step
	2.9		Dimensional PDEs: Problem Formulation
	2.10		timensional PDE with No Mixed Derivatives
		2.10.1	Theta Method
		2.10.2	The Alternating Direction Implicit (ADI) Method
	0.11	2.10.3	Boundary Conditions and Other Issues
	2.11		timensional PDE with Mixed Derivatives
		2.11.1	Orthogonalization of the PDE
	0.10	2.11.2	Predictor-Corrector Scheme
	2.12	PDEs (	of Arbitrary Order

				Contents	XIII			
3	Mo	nte Ca	rlo Meth	$\mathrm{ods} \ldots \ldots$	93			
	3.1				93			
		3.1.1		on of Random Samples	95			
			3.1.1.1	Inverse Transform Method	96			
			3.1.1.2	Acceptance-Rejection Method	97			
			3.1.1.3	Composition	99			
		3.1.2	Correlate	ed Gaussian Samples	100			
			3.1.2.1	Cholesky Decomposition	101			
			3.1.2.2	Eigenvalue Decomposition	102			
		3.1.3	Principal	Components Analysis (PCA)	103			
	3.2	Genera	ation of Sa	mple Paths	104			
		3.2.1	Example	: Asian Basket Options in Black-Scholes				
			Economy	·	104			
		3.2.2	Discretiz	ation Schemes, Convergence, and Stability	106			
		3.2.3	The Eule	er Scheme	108			
			3.2.3.1	Linear-Drift SDEs	110			
			3.2.3.2	Log-Euler Scheme	110			
		3.2.4	_	licit Euler Scheme	111			
			3.2.4.1	Implicit Diffusion Term	112			
		3.2.5		r-Corrector Schemes	113			
		3.2.6		or Expansions and Higher-Order Schemes.	114			
			3.2.6.1	Ordinary Taylor Expansion of ODEs	115			
			3.2.6.2	Ito-Taylor Expansions	116			
			3.2.6.3	Milstein Second-Order Discretization				
			0.1 0	Scheme	117			
		3.2.7		cond-Order Schemes	119			
		3.2.8		Monte Carlo Error	$\frac{120}{122}$			
		3.2.9	Sampling of Continuous Process Extremes					
		3.2.10		d Bridge Construction of Brownian	100			
				Paths	126			
			3.2.10.1	Brownian Bridge and Quasi-Random	196			
			3.2.10.2	Sequences	126			
	3.3	Consit		outations	128 129			
	ა.ა	3.3.1		ifference Estimates	129 $129$			
		5.5.1	3.3.1.1	Black-Scholes Delta	129			
			3.3.1.1 $3.3.1.2$	General Case	131			
		3.3.2		Estimate	133			
		0.0.2	3.3.2.1	Black-Scholes Delta	133			
			3.3.2.2	General Case	134			
			3.3.2.3	Sensitivity Path Generation	136			
		3.3.3		od Ratio Method	136			
		0.0.0	3.3.3.1	Black-Scholes Delta	137			
			3.3.3.2	General Case	138			
			3 3 3 3	Euler Schemes	138			

			3.3.3.4 Some Remarks	139
	3.4	Varian	nce Reduction Techniques	140
		3.4.1	Variance Reduction and Efficiency	141
		3.4.2	Antithetic Variates	141
			3.4.2.1 The Gaussian Case	141
			3.4.2.2 General Case	143
		3.4.3	Control Variates	143
			3.4.3.1 Basic Idea	143
			3.4.3.2 Non-Linear Controls	145
		3.4.4	Importance Sampling	146
			3.4.4.1 Basic Idea	146
			3.4.4.2 Density Formulation	147
			3.4.4.3 Importance Sampling and SDEs	149
			3.4.4.4 More on SDE Path Simulation	150
			3.4.4.5 Rare Event Simulation and Linearization	152
	3.5	Some	Notes on Bermudan Security Pricing	156
		3.5.1	Basic Idea	156
		3.5.2	Parametric Lower Bound Methods	157
		3.5.3	Parametric Lower Bound: An Example	158
		3.5.4	Regression-Based Lower Bound	159
		3.5.5	Upper Bound Methods	160
		3.5.6	Confidence Intervals	161
		3.5.7	Other Methods	162
	3.A	Appen	ndix: Constants for $\Phi^{-1}$ Algorithm	163
4	Fun	damer	ntals of Interest Rate Modeling	165
_	4.1		Income Notations	165
		4.1.1	Bonds and Forward Rates	165
		4.1.2	Futures Rates	167
		4.1.3	Annuity Factors and Par Rates	168
	4.2	Fixed	Income Probability Measures	169
		4.2.1	Risk Neutral Measure	170
		4.2.2	T-Forward Measure	172
		4.2.3	Spot Measure	173
		4.2.4	Terminal and Hybrid Measures	174
		4.2.5	Swap Measures	175
	4.3	Multi-	Currency Markets	176
		4.3.1	Notations and FX Forwards	176
		4.3.2	Risk Neutral Measures	177
		4.3.3	Other Measures	178
	4.4	The H	IJM Analysis	179
		4.4.1	Bond Price Dynamics	179
		4.4.2	Forward Rate Dynamics	180
		4.4.3	Short Rate Process	181
	4.5	-	ples of HJM Models	182

			Contents	XV
		4.5.1	The Gaussian Model	. 182
		4.5.2	Gaussian HJM Models with Markovian Short Rate	e 185
		4.5.3	Log-Normal HJM Models	. 187
5	Fixe		ome Instruments	
	5.1		Income Markets and Participants	
	5.2		cates of Deposit and Libor Rates	
	5.3		rd Rate Agreements (FRA)	
	5.4		ollar Futures	
	5.5		for-Floating Swaps	
	5.6		in-Arrears Swaps	
	5.7	-	ging Swaps	
	5.8	_	and Floors	
	5.9		l Caps and Floors	
	5.10		ean Swaptions	
		5.10.1	1	
			Swaps, Caps and Floors	
			dan Swaptions	
	5.13	Exotic	Swaps and Structured Notes	
		5.13.1	1	
		5.13.2	CMS-Based Exotic Swaps	
		5.13.3	Multi-Rate Exotic Swaps	
		5.13.4	Range Accruals	
		5.13.5	Path-Dependent Swaps	
	5.14	Callab	le Libor Exotics	
		5.14.1	Definitions	
		5.14.2	Pricing Callable Libor Exotics	. 213
		5.14.3	Types of Callable Libor Exotics	. 214
		5.14.4	Callable Snowballs	. 214
		5.14.5	CLEs Accreting at Coupon Rate	
		5.14.6	Multi-Tranches	. 215
	5.15	TARN	s and Other Trade-Level Features	. 215
		5.15.1	Knock-out Swaps	
		5.15.2	TARNs	. 216
		5.15.3	Global Cap	. 217
		5.15.4	Global Floor	. 217
		5.15.5	Pricing and Trade Representation Challenges	. 217
	5.16	Volatil	ity Derivatives	. 218
		5.16.1	Volatility Swaps	. 218
		5.16.2	Volatility Swaps with a Shout	
		5.16.3	Min-Max Volatility Swaps	
		5.16.4	Forward Starting Options and Other Forward	
			Volatility Contracts	. 220
	5.A	Appen	dix: Day Counting Rules and Other Trivia	
		5.A.1	Libor Rate Definitions	
		5.A.2	Swap Payments	

#### Part II Vanilla Models

6.1		ions and Problem Definition	
	6.1.1	Discount Curves	
	6.1.2	Matrix Formulation	
	6.1.3	Construction Principles and Yield Curves	
6.2	Yield	Curve Fitting with N-Knot Splines	
	6.2.1	$C^0$ Yield Curves: Bootstrapping	
		6.2.1.1 Piecewise Linear Yields	
		6.2.1.2 Piecewise Flat Forward Rates	
	6.2.2	$C^1$ Yield Curves: Hermite Splines	
	6.2.3	$C^2$ Yield Curves: Twice Differentiable Cubic	
		Splines	
	6.2.4	$C^2$ Yield Curves: Twice Differentiable Tension	
		Splines	
6.3	Non-P	Parametric Optimal Yield Curve Fitting	
	6.3.1	Norm Specification and Optimization	
	6.3.2	Choice of $\lambda$	
	6.3.3	Example	
6.4	Manag	ging Yield Curve Risk	
	6.4.1	Par-Point Approach	
	6.4.2	Forward Rate Approach	
	6.4.3	From Risks to Hedging: The Jacobian Approach	
	6.4.4	Cumulative Shifts and other Common Tricks	
6.5		as Topics in Discount Curve Construction	
	6.5.1	Curve Overlays and Turn-of-Year Effects	
	6.5.2	Cross-Currency Curve Construction	
		6.5.2.1 Basic Problem	
		6.5.2.2 Separation of Discount and Forward	
		Rate Curves	
		6.5.2.3 Cross-Currency Basis Swaps	
		6.5.2.4 Modified Curve Construction Algorithm	
	6.5.3	Tenor Basis and Multi-Index Curve Group	
		Construction	
6.A		ndix: Spline Theory	
	6.A.1	Hermite Spline Theory	
	6.A.2	$C^2$ Cubic Splines	
	6.A.3	$C^2$ Exponential Tension Splines	
Var	nilla M	odels with Local Volatility	
7.1	Gener	al Framework	
	7.1.1	Model Dynamics	
	7.1.2	Volatility Smile and Implied Density	

		Contents
		7.1.3 Choice of $\varphi$
	7.2	CEV Model
		7.2.1 Basic Properties
		7.2.2 Call Option Pricing
		7.2.3 Regularization
		7.2.4 Displaced Diffusion Models
	7.3	Quadratic Volatility Model
		7.3.1 Case 1: Two Real Roots to the Left of $S(0)$
		7.3.2 Case 2: One Real Root to the Left of $S(0)$
		7.3.3 Extensions and Other Root Configurations
	7.4	Finite Difference Solutions for General $\varphi$
		7.4.1 Multiple $\lambda$ and $T$
		7.4.2 Forward Equation for Call Options
	7.5	Asymptotic Expansions for General $\varphi$
		7.5.1 Expansion around Displaced Log-Normal Process .
		7.5.2 Expansion around Gaussian Process
	7.6	Extensions to Time-Dependent $\varphi$
		7.6.1 Separable Case
		7.6.2 Skew Averaging
		7.6.2.1 Examples
		7.6.2.2 A Caveat About the Process Domain
		7.6.3 Skew and Convexity Averaging by Small-Noise
		Expansion
		7.6.4 Numerical Example
8	Var	nilla Models with Stochastic Volatility I
	8.1	Model Definition
	8.2	Model Parameters
	8.3	Basic Properties
	8.4	Fourier Integration
		8.4.1 General Theory
		8.4.2 Applications to SV Model
		8.4.3 Numerical Implementation
		8.4.4 Refinements of Numerical Implementation
		8.4.5 Fourier Integration for Arbitrary European Payoffs
	8.5	Integration in Variance Domain
	8.6	CEV-Type Stochastic Volatility Models and SABR
	8.7	Numerical Examples: Volatility Smile Statics
	8.8	Numerical Examples: Volatility Smile Dynamics
	8.9	Hedging in Stochastic Volatility Models
		8.9.1 Hedge Construction, Delta and Vega
		8.9.2 Minimum Variance Delta Hedging
		8.9.3 Minimum Variance Hedging: an Example
	8.A	Appendix: General Volatility Processes

## XVIII Contents

9	Vanilla Models with Stochastic Volatility II							
	9.1	Fourier Integration with Time-Dependent Parameters						
	9.2	Asymptotic Expansion with Time-Dependent Volatility .						
	9.3	Averaging Methods						
		9.3.1	Volatility	Averaging	367			
		9.3.2	Skew Av	eraging	369			
		9.3.3		y of Variance Averaging	370			
		9.3.4	Calibrat	ion by Parameter Averaging	372			
	9.4	PDE N	Method		377			
		9.4.1	PDE For	mulation	377			
		9.4.2	Range for	or Stochastic Variance	378			
		9.4.3	Discretiz	ing Stochastic Variance	379			
		9.4.4	Boundar	y Conditions for Stochastic Variance	381			
		9.4.5	Range for	or Underlying	382			
		9.4.6	Discretiz	ing the Underlying	383			
	9.5	Monte Carlo Method						
		9.5.1	Exact Si	mulation of Variance Process	384			
		9.5.2	Biased T	Caylor-Type Schemes for Variance Process	385			
			9.5.2.1	Euler Schemes	385			
			9.5.2.2	Higher-Order Schemes	385			
		9.5.3	Moment	Matching Schemes for Variance Process	386			
			9.5.3.1	Log-normal Approximation	386			
			9.5.3.2	Truncated Gaussian	387			
			9.5.3.3	Quadratic-Exponential	388			
			9.5.3.4	Summary of QE Algorithm	390			
		9.5.4	Broadie-	Kaya Scheme for the Underlying	390			
		9.5.5	Other So	chemes for the Underlying	392			
			9.5.5.1	Taylor-Type Schemes	392			
			9.5.5.2	Simplified Broadie-Kaya	392			
			9.5.5.3	Martingale Correction	392			
	9.A			of Proposition 9.3.4	393			
	9.B	Appendix: Coefficients for Asymptotic Expansion						

# **VOLUME II Term Structure Models**

Par	rt III Term	Structur	e Models	
10	One-Facto	r Short F	Cate Models I	401
			Gaussian Short Rate Model	402
	10.1.1		ee Model	402
		10.1.1.1	Notations and First Steps	402
		10.1.1.2	Fitting the Term Structure of	
			Discount Bonds	403
		10.1.1.3	Analysis and Comparison with HJM	
			Approach	405
	10.1.2	The Mea	n-Reverting GSR Model	407
		10.1.2.1	The Vasicek Model	407
		10.1.2.2	The General One-Factor GSR Model	409
		10.1.2.3	Time-Stationarity and Caplet Hump	412
	10.1.3	European	Option Pricing	414
		10.1.3.1	The Jamshidian Decomposition	414
		10.1.3.2	Gaussian Swap Rate Approximation	416
	10.1.4	_	Calibration	417
	10.1.5		fference Methods	418
		10.1.5.1	PDE and Spatial Boundary Conditions.	419
		10.1.5.2	Determining Spatial Boundary	
			Conditions from PDE	420
		10.1.5.3	Upwinding	421
	10.1.6		arlo Simulation	421
		10.1.6.1	Exact Discretization	421
		10.1.6.2	Approximate Discretization	423
		10.1.6.3	Using other Measures for Simulation	424
			Factor Model	425
	10.2.1		finitions	425
		10.2.1.1	SDE	425
		10.2.1.2	Regularity Issues	426
		10.2.1.3	Volatility Skew	426
		10.2.1.4	Time-Dependent Parameters	427
	10.2.2		Bond Pricing and Extended Transform	427
		10.2.2.1	Constant Parameters	428
		10.2.2.2	Piecewise Constant Parameters	430
	10.2.3		Bond Calibration	431
		10.2.3.1	Change of Variables	431
	400.	10.2.3.2	Algorithm for $\omega(t)$	432
	10.2.4	Luropear	Option Pricing	433

XX	Contents

	10.2.5	Swaption Calibration	435
		10.2.5.1 Basic Problem	435
		10.2.5.2 Calibration Algorithm	436
	10.2.6	Quadratic One-Factor Model	437
	10.2.7	Numerical Methods for the Affine Short Rate	
		Model	437
11	One-Factor	r Short Rate Models II	439
	11.1 Log-No	ormal Short Rate Models	439
	11.1.1	The Black-Derman-Toy Model	439
	11.1.2	Black-Karasinski Model	441
	11.1.3	Issues in Log-Normal Models	441
	11.1.4	Sandmann-Sondermann Transformation	442
	11.2 Other	Short Rate Models	445
	11.2.1	Power-Type Models and Empirical Model	
		Estimation	445
	11.2.2	The Black Shadow Rate Model	446
	11.2.3	Spanned and Unspanned Stochastic Volatility:	
		the Fong and Vasicek Model	448
	11.3 Numer	rical Methods for General One-Factor Short Rate	
	Models	3	449
	11.3.1	Finite Difference Methods	450
	11.3.2	Calibration to Initial Yield Curve	451
		11.3.2.1 Forward Induction	452
		11.3.2.2 Forward-from-Backward Induction	453
		11.3.2.3 Yield Curve and Volatility Calibration .	455
		11.3.2.4 The Dybvig Parameterization	457
		11.3.2.5 Link to HJM Models	458
		11.3.2.6 The Hagan and Woodward	
		Parameterization	459
	11.3.3	Monte Carlo Simulation	462
		11.3.3.1 SDE Discretization	462
		11.3.3.2 Practical Issues with Monte Carlo	
		Methods	464
	11.A Appen	dix: Markov-Functional Models	466
	11.A.1	State Process and Numeraire Mapping	466
	11.A.2	Libor MF Parameterization	467
	11.A.3	Swap MF Parameterization	469
	11.A.4	Non-Parametric Calibration	470
	11.A.5	Numerical Implementation	471
	11.A.6	Comments and Comparisons	472

	Contents
Multi-Factor Short Rat	e Models
12.1 The Gaussian Model	
	from Separability Condition
	an-Reverting State Variables
	ther Changes of Variables
	elopment
	agonalization of Mean Reversion
	trix
	tructure
12.1.4 The Two-Fact	tor Gaussian Model
	me Basics
	riance and Correlation Structure
	atility Hump
	other Formulation of the
	o-Factor Model
	Statistical Gaussian Model
	ing
	nshidian Decomposition
	ussian Swap Rate Approximation
	a Benchmark Rates
	Simulation
	nce Methods
	ues
	d Prices
12.2.5 Some Concret	e Models
	ng-Vasicek Model
	ngstaff-Schwartz Model
	lti-Factor CIR Models
12.2.6 Brief Notes or	Option Pricing
	ian Model
12.3.1 Quadratic Ga	ussian Models are Affine
12.3.2 The Basics	
	ion
12.3.3.1 Sm	ile Generation
12.3.3.2 Qu	adratic Term
	ear Term
	ing
_	te Vector Distribution Under the
	nuity Measure
	act Pricing of European Swaptions
	proximations for European Swaptions

#### XXII Contents

		12.3.6	Spanned	Stochastic Volatility	528
		12.3.7	-	al Methods	528
	12.A	Append	dix: Quadı	ratic Forms of Gaussian Vectors	528
13	The	Quasi	-Gaussiaı	n Model	533
	13.1	One-Fa	ctor Quas	i-Gaussian Model	533
		13.1.1		1	533
		13.1.2	Local Vol	latility	535
		13.1.3	Swap Rat	te Dynamics	536
		13.1.4		nate Local Volatility Dynamics for Swap	
			Rate		537
			13.1.4.1	Simple Approximation	538
			13.1.4.2	Advanced Approximation	538
		13.1.5		ocal Volatility	541
		13.1.6		ocal Volatility for a Swaption Strip	543
		13.1.7		Calibration	544
		13.1.8	Mean Re	version Calibration	546
			13.1.8.1	Effects of Mean Reversion	546
			13.1.8.2	Calibrating Mean Reversion to	
				Volatility Ratios	548
			13.1.8.3	Calibrating Mean Reversion to	
				Inter-Temporal Correlations	551
			13.1.8.4	Final Comments on Mean Reversion	
				Calibration	553
		13.1.9		al Methods	554
			13.1.9.1	Direct Integration	554
			13.1.9.2	Finite Difference Methods	556
			13.1.9.3	Monte Carlo Simulation	559
			13.1.9.4	Single-State Approximations	559
	13.2			i-Gaussian Model with Stochastic	
			•		563
		13.2.1		1	563
		13.2.2		te Dynamics	564
		13.2.3		Calibration	566
		13.2.4		version Calibration	567
		13.2.5		Correlation	567
		13.2.6		Monte Carlo Methods	568
	13.3		•	asi-Gaussian Model	568
		13.3.1		Multi-Factor Model	568
		13.3.2		d Stochastic Volatility Parameterization .	570
		13.3.3		te Dynamics and Approximations	572
		13.3.4		Calibration	577
		13.3.5		versions, Correlations, and Numerical	F == 0
	10 4				578
	13.A	Appene	aix: Densit	ty Approximation	579

				Contents	XXIII
		13.A.1	Simplified Forward Measure Dynamics		579
			Effective Volatility		
		13.A.3	The Forward Equation for Call Options		581
			Asymptotic Expansion		
		13.A.5	Proof of Theorem 13.1.14		583
14	The	Libor	Market Model I		585
	14.1	Introdu	action and Setup		586
		14.1.1	Motivation and Historical Notes		
		14.1.2	Tenor Structure		587
	14.2	LM Dy	rnamics and Measures		587
		14.2.1	Setting		587
		14.2.2	Probability Measures		
		14.2.3	Link to HJM Analysis		
		14.2.4	Separable Deterministic Volatility Funct	ion	592
		14.2.5	Stochastic Volatility		
		14.2.6	Time-Dependence in Model Parameters		597
	14.3	Correla	ation		
		14.3.1	Empirical Principal Components Analys		
			14.3.1.1 Example: USD Forward Rates	3	599
		14.3.2	Correlation Estimation and Smoothing		
			14.3.2.1 Example: Fit to USD Data		
		14.3.3	Negative Eigenvalues		
		14.3.4	Correlation PCA		
			14.3.4.1 Example: USD Data		607
			14.3.4.2 Poor Man's Correlation PCA		
	14.4	Pricing	g of European Options		608
		14.4.1	Caplets		609
		14.4.2	Swaptions		
		14.4.3	Spread Options		
			14.4.3.1 Term Correlation		
			14.4.3.2 Spread Option Pricing		615
	14.5	Calibra	ation		615
		14.5.1	Basic Principles		615
		14.5.2	Parameterization of $\ \lambda_k(t)\ $		616
		14.5.3	Interpolation on the Whole Grid		
		14.5.4	Construction of $\lambda_k(t)$ from $\ \lambda_k(t)\ $		619
			14.5.4.1 Covariance PCA		
			14.5.4.2 Correlation PCA		620
			14.5.4.3 Discussion and Recommendat	ion	621
		14.5.5	Choice of Calibration Instruments		
		14.5.6	Calibration Objective Function		
		14.5.7	Sample Calibration Algorithm		
		14.5.8	Speed-Up Through Sub-Problem Splittin		
		14.5.9	Correlation Calibration to Spread Optio		

## XXIV Contents

	14.5.10	) Volatility	Skew Calibration
14.6	6 Monte	Carlo Sim	ulation
	14.6.1	Euler-Ty	pe Schemes
		14.6.1.1	Analysis of Computational Effort
		14.6.1.2	Long Time Steps
		14.6.1.3	Notes on the Choice of Numeraire
	14.6.2	Other Sir	mulation Schemes
		14.6.2.1	Special-Purpose Schemes with Drift
			Predictor-Corrector
		14.6.2.2	Euler Scheme with Predictor-Corrector .
		14.6.2.3	Lagging Predictor-Corrector Scheme
		14.6.2.4	Further Refinements of Drift Estimation
		14.6.2.5	Brownian-Bridge Schemes and Other
			Ideas
		14.6.2.6	High-Order Schemes
	14.6.3	_	le Discretization
		14.6.3.1	Deflated Bond Price Discretization
	1101	14.6.3.2	Comments and Alternatives
	14.6.4		Reduction
		14.6.4.1	Antithetic Sampling
		14.6.4.2	Control Variates
		14.6.4.3	Importance Sampling
5 The	e Libor	Market 1	Model II
15.1	Interpo	olation	
	15.1.1	Back Stu	b, Simple Interpolation
	15.1.2	Back Stu	b, Arbitrage-Free Interpolation
	15.1.3	Back Stu	b, Gaussian Model
	15.1.4	Front Stu	ıb, Zero Volatility
	15.1.5	Front Stu	ıb, Exogenous Volatility
	15.1.6	Front Stu	ıb, Simple Interpolation
	15.1.7	Front Stu	ıb, Gaussian Model
15.2	2 Advan	ced Swapti	ion Pricing via Markovian Projection
	15.2.1		d Formula for Swap Rate Volatility
	15.2.2		d Formula for Swap Rate Skew
	15.2.3		l Smile Calibration in LM Models
			I Models
15.4	I Swap I	Market Mo	odels
15.5	Evolvi:	ng Separat	e Discount and Forward Rate Curves
	15.5.1		as
	15.5.2		gension
	15.5.3		ons to LM Models
	15.5.4		istic Spread
			Non-Zero Correlation
15.7	Multi-	Stochastic	Volatility Extensions

	Contents	XXV
15.7.1	Introduction	683
15.7.2	Setup	684
15.7.3	Pricing Caplets and Swaptions	685
15.7.4	Spread Options	686
15.7.5	Another Use of Multi-Dimensional Stochastic	
	Volatility	687

# VOLUME III Products and Risk Management

Pai	rt IV	Produ	ıcts	
16	Sing	gle-Rat	e Vanilla Derivatives	691
	16.1	Europe	ean Swaptions	691
		16.1.1	Smile Dynamics	692
		16.1.2	Adjustable Backbone	693
		16.1.3	Stochastic Volatility Swaption Grid	696
		16.1.4	Calibrating Stochastic Volatility Model to	
			Swaptions	697
		16.1.5	Some Other Interpolation Rules	699
	16.2	Caps a	nd Floors	700
		16.2.1	Basic Problem	700
		16.2.2	Setup and Norms	701
		16.2.3	Calibration Procedure	702
	16.3	Termin	nal Swap Rate Models	703
		16.3.1	TSR Basics	703
		16.3.2	Linear TSR Model	705
		16.3.3	Exponential TSR Model	708
		16.3.4	Swap-Yield TSR Model	709
	16.4	Libor-i	n-Arrears	710
	16.5	Libor-v	with-Delay	713
		16.5.1	Swap-Yield TSR Model	714
		16.5.2	Other Terminal Swap Rate Models	715
		16.5.3	Approximations Inspired by Term Structure	
			Models	715
		16.5.4	Applications to Averaging Swaps	716
	16.6	CMS a	nd CMS-Linked Cash Flows	717
		16.6.1	The Replication Method for CMS	718
		16.6.2	Annuity Mapping Function as a Conditional	
			Expected Value	720
		16.6.3	Swap-Yield TSR Model	722
		16.6.4	Linear and Other TSR Models	722
		16.6.5	The Quasi-Gaussian Model	724
		16.6.6	The Libor Market Model	725
		16.6.7	Correcting Non-Arbitrage-Free Methods	728
		16.6.8	Impact of Annuity Mapping Function and Mean	
			Reversion	729
		16.6.9	CDF and PDF of CMS Rate in Forward Measure .	730
		16.6.10	SV Model for CMS Rate	734

		16.6.11	Dynamics of CMS Rate in Forward Measure	735
			Cash-Settled Swaptions	738
	16.7		CMS	740
		16.7.1	Overview	740
		16.7.2	Modeling the Joint Distribution of Swap Rate	
			and Forward Exchange Rate	742
		16.7.3	Normalizing Constant and Final Formula	743
	16.8		llar Futures	744
		16.8.1	Fundamental Results on Futures	745
		16.8.2	Motivations and Plan	747
		16.8.3	Preliminaries	748
		16.8.4	Expansion Around the Futures Value	748
		16.8.5	Forward Rate Variances	751
		16.8.6	Forward Rate Correlations	753
		16.8.7	The Formula	754
	16.9		ity and Moment Explosions	755
17	Mul	ti-Rate	e Vanilla Derivatives	759
	17.1	Introdu	action to Multi-Rate Vanilla Derivatives	759
	17.2	Margin	al Distributions and Reference Measure	761
	17.3	Depend	lence Structure via Copulas	762
		17.3.1	Introduction to Gaussian Copula Method	762
		17.3.2	General Copulas	764
		17.3.3	Archimedean Copulas	766
		17.3.4	Making Copulas from Other Copulas	767
	17.4	Copula	Methods for CMS Spread Options	770
		17.4.1	Normal Model for the Spread	770
		17.4.2	Gaussian Copula for Spread Options	771
		17.4.3	Spread Volatility Smile Modeling with the Power	
			Gaussian Copula	774
		17.4.4	Copula Implied From Spread Options	775
	17.5	Rates (	Observed at Different Times	778
	17.6	Numeri	cal Methods for Copulas	779
		17.6.1	Numerical Integration Methods	780
		17.6.2	Dimensionality Reduction for CMS Spread Options	783
		17.6.3	Dimensionality Reduction for Other Multi-Rate	
			Derivatives	785
		17.6.4	Dimensionality Reduction by Conditioning	787
		17.6.5	Dimensionality Reduction by Measure Change	791
		17.6.6	Monte Carlo Methods	793
	17.7	Limitat	ions of the Copula Method	795
			stic Volatility Modeling for Multi-Rate Options	796
		17.8.1	Measure Change by Drift Adjustment	797
		17.8.2	Measure Change by CMS Caplet Calibration	798
			Impact of Correlations on the Spread Smile	799

#### XXVIII Contents

		17.8.4	Connectio	on to Term Structure Models	800
	17.9	CMS S	pread Opti	ions in Term Structure Models	802
			-	rket Model	802
		17.9.2		Gaussian Model	804
	17.A	Append		d Correlation in Displaced Log-Normal	
					805
				ries	805
				og-Normal Correlation	806
				merical Results	807
18	Call	able Li	bor Exot	ics	809
	18.1	Model	Calibration	n for Callable Libor Exotics	809
		18.1.1	Risk Facto	ors for CLEs	810
		18.1.2		oice and Calibration	813
	18.2	Valuati			814
		18.2.1		ries	814
		18.2.2	Recursion	for Callable Libor Exotics	815
		18.2.3	Marginal	Exercise Value Decomposition	816
	18.3	Monte		ation	817
		18.3.1	Regression	n-Based Valuation of CLEs, Basic Scheme	817
		18.3.2	Regression	n for Underlying	819
		18.3.3	Valuing C	LE as a Cancelable Note	821
		18.3.4	Using Reg	gressed Variables for Decision Only	822
		18.3.5	Regression	n Valuation with Boundary Optimization	824
		18.3.6	Lower Bo	und via Regression Scheme	825
		18.3.7	Iterative I	Improvement of Lower Bound	827
		18.3.8	Upper Bo	und	830
			18.3.8.1	Basic Ideas	830
			18.3.8.2	Nested Simulation (NS) Algorithm	831
			18.3.8.3	Bias and Computational Cost of NS	
				Algorithm	834
			18.3.8.4	Confidence Intervals and Practical	
				Usage	836
			18.3.8.5	Non-Analytic Exercise Values	837
			18.3.8.6	Improvements to NS Algorithm	839
			18.3.8.7	Other Upper Bound Algorithms	841
		18.3.9	Regression	n Variable Choice	842
			18.3.9.1	State Variables Approach	842
			18.3.9.2	Explanatory Variables	843
			18.3.9.3	Explanatory Variables with Convexity .	846
		18.3.10	Regression	Implementation	848
			18.3.10.1	Automated Explanatory Variable	
				Selection	848
			18.3.10.2	Suboptimal Point Exclusion	850
			18.3.10.3	Two Step Regression	851

			18.3.10.4 Robust Implementation of Regression Algorithm
	18 /	Voluet	ion with Low–Dimensional Models
	10.4	18.4.1	Single-Rate Callable Libor Exotics
		18.4.2	Calibration Targets for the Local Projection
		10.4.2	Method
		18.4.3	Review of Suitable Local Models
		18.4.4	
		18.4.5	PDE Methods for Path-Dependent CLEs
		10.4.0	18.4.5.1 CLEs Accreting at Coupon Rate
			18.4.5.2 Snowballs
19	Ber	mudan	Swaptions
10			tions
			Projection Method
			Calibration
			izing, Accreting, Other Non-Standard Swaptions
	10.1	19.4.1	Relationship Between Non-Standard and
		10.1.1	Standard Swap Rates
		19.4.2	Same-Tenor Approach
		19.4.3	Representative Swaption Approach
		19.4.4	Basket Approach
		19.4.5	Super-Replication for Non-Standard Bermudan
		10.1.0	Swaptions
		19.4.6	Zero-Coupon Bermudan Swaptions
		19.4.7	American Swaptions
		10.1.1	19.4.7.1 American Swaptions vs. High-
			Frequency Bermudan Swaptions
			19.4.7.2 The Proxy Libor Rate Method
			19.4.7.3 The Libor-as-Extra-State Method
		19.4.8	Mid-Coupon Exercise
	19.5		Swaps
		19.5.1	Purely Global Bounds
		19.5.2	Purely Local Bounds
		19.5.3	Marginal Exercise Value Decomposition
		19.5.4	Narrow Band Limit
	19.6		Carlo Valuation
	_5.5		Regression Methods
		19.6.2	Parametric Boundary Methods
		10.0.2	19.6.2.1 Sample Exercise Strategies for
			Bermudan Swaptions
			19.6.2.2 Some Numerical Tests
			19.6.2.3 Additional Comments
	19.7	Other	

## XXX Contents

	1	19.7.1	Robust Bermudan Swaption Hedging with European Swaptions	904
	1	19.7.2	Carry and Exercise	904
	_	19.7.2		907
			Fast Pricing via Exercise Premia Representation .	912
			lix: Forward Volatility and Correlation	
			lix: A Primer on Moment Matching	913
			Basics BSM M. 1.1	913
			Example 1: Asian Option in BSM Model Example 2: Basket Option in BSM Model	914 916
20			olatility Swaps, and Other Derivatives	919
			D.C	919
		20.1.1	Definitions and Examples	919
	2	20.1.2	Valuation and Risk with Globally Calibrated	0.01
		20.1.0	Models	921
		20.1.3	Local Projection Method	922
		20.1.4	Volatility Smile Effects	923
		20.1.5	PDE for TARNs	925
			ty Swaps	927
		20.2.1	Local Projection Method	928
		20.2.2	Shout Options	929
		20.2.3	Min-Max Volatility Swaps	932
		20.2.4	Impact of Volatility Dynamics on Volatility Swaps	934
	20.3 I	Forward	d Swaption Straddles	939
21			del Adjustments	945
	21.1 A	Adjusti	ng the Model	946
	2	21.1.1	Calibration to Coupons	946
	2	21.1.2	Adjusters	948
	2	21.1.3	Path Re-Weighting	950
	2	21.1.4	Proxy Model Method	955
	2	21.1.5	Asset-Based Adjustments	957
	2	21.1.6	Mapping Function Adjustments	959
	21.2 A	Adjusti	ng the Market	959
	21.3 A	Adjusti	ng the Trade	960
	2	21.3.1	Fee Adjustments	961
	2	21.3.2	Fee Adjustment Impact on Exotic Derivatives	962
	2	21.3.3	Strike Adjustment	963

## Part V Risk Management

	Contents	XXXI
22	Introduction to Risk Management	969
	22.1 Risk Management and Sensitivity Computations	970
	22.1.1 Basic Information Flow	970
	22.1.2 Risk: Theory and Practice	972
	22.1.3 Example: the Black-Scholes Model	974
	22.1.4 Example: Black-Scholes Model with	
	Time-Dependent Parameters	977
	22.1.5 Actual Risk Computations	979
	22.1.6 What about $\Theta_{\text{prm}}$ and $\Theta_{\text{num}}$ ?	980
	22.1.7 A Note on Trading P&L and the Computation	
	of Implied Volatility	981
	22.2 P&L Analysis	984
	22.2.1 P&L Predict	985
	22.2.2 P&L Explain	987
	22.2.2.1 Waterfall Explain	987
	22.2.2.2 Bump-and-Reset Explain	988
	22.3 Value-at-Risk	989
	22.A Appendix: Alternative Proof of Lemma 22.1.1	992
23	Payoff Smoothing and Related Methods	995
	23.1 Issues with Discretization Schemes	995
	23.1.1 Problems with Grid Dimensioning	996
	23.1.2 Grid Shifts Relative to Payout	996
	23.1.3 Additional Comments	999
	23.2 Basic Techniques	1000
	23.2.1 Adaptive Integration	1000
	23.2.2 Adding Singularities to the Grid	1001
	23.2.3 Singularity Removal	1003
	23.2.4 Partial Analytical Integration	1004
	23.3 Payoff Smoothing For Numerical Integration and PDEs	1006
	23.3.1 Introduction to Payoff Smoothing	1006
	23.3.2 Payoff Smoothing in One Dimension	1008
	23.3.2.1 Box Smoothing	1009
	23.3.2.2 Other Smoothing Methods	1012
	23.3.3 Payoff Smoothing in Multiple Dimensions	1013
	23.4 Payoff Smoothing for Monte Carlo	1016
	23.4.1 Tube Monte Carlo for Digital Options	1016
	23.4.2 Tube Monte Carlo for Barrier Options	1018
	23.4.3 Tube Monte Carlo for Callable Libor Exotics	1023
	23.4.4 Tube Monte Carlo for TARNs	1023
	23.A Appendix: Delta Continuity of Singularity-Enlarged	
	Grid Method	1024
	23.B Appendix: Conditional Independence for Tube Monte	
	Carlo	1026

#### XXXII Contents

24	Patl	hwise I	Differentiation	1029
	24.1	Pathwi	ise Differentiation: Foundations	1029
		24.1.1	Callable Libor Exotics	1029
			24.1.1.1 CLE Greeks	1030
			24.1.1.2 Keeping the Exercise Time Constant	1032
			24.1.1.3 Noise in CLE Greeks	1033
		24.1.2	Barrier Options	1034
	24.2	Pathwi	ise Differentiation for PDE Based Models	1038
		24.2.1	Model and Setup	1038
		24.2.2	Bucketed Deltas	1039
		24.2.3	Survival Density	1042
	24.3	Pathwi	ise Differentiation for Monte Carlo Based Models	1045
		24.3.1	Pathwise Derivatives of Forward Libor Rates	1045
		24.3.2	Pathwise Deltas of European Options	1048
			24.3.2.1 Pathwise Deltas of the Numeraire	1048
			24.3.2.2 Pathwise Deltas of the Payoff	1049
		24.3.3	Adjoint Method For Greeks Calculation	1050
		24.3.4	Pathwise Delta Approximation for Callable	
			Libor Exotics	1052
	24.4	Notes	on Likelihood Ratio and Hybrid Methods	1054
<b>25</b>			ee Sampling and Control Variates	1057
			tance Sampling In Short Rate Models	1057
	25.2	·	Smoothing by Importance Sampling	1059
		25.2.1	Binary Options	1059
		25.2.2	TARNs	1062
		25.2.3	Removing the First Digital	1062
		25.2.4	Smoothing All Digitals by One-Step Survival	4000
		2525	Conditioning	1063
		25.2.5	Simulating Under the Survival Measure Using	1000
		05.0.0	Conditional Gaussian Draws	1066
		25.2.6	Generalized Trigger Products in Multi-Factor	1000
	05.0	N.F. 1.1	LM Models	1068
	25.3		-Based Control Variates	1071
		25.3.1	Low-Dimensional Markov Approximation for LM	1070
		25.23	models	1072
		25.3.2	Two-Dimensional Extension	1075
		25.3.3	Approximating Volatility Structure	1076 $1078$
	25 4	25.3.4 Instrum	ment-Based Control Variates	1078
			ment-based Control Variates	1080
				1084 $1087$
	∠ე.0	Contro	ol Variates and Risk Stability	1001

26	veg	as in Libor Market Models	1089
	26.1	Basic Problem of Vega Computations	1089
	26.2	Review of Calibration	1091
		Vega Calculation Methods	1092
		26.3.1 Direct Vega Calculations	1092
		26.3.1.1 Definition and Analysis	1092
		26.3.1.2 Numerical Example	1095
		26.3.2 What is a Good Vega?	1096
		26.3.3 Indirect Vega Calculations	1099
		26.3.3.1 Definition and Analysis	1099
		26.3.3.2 Numerical Example and Performance	1100
		Analysis	1102
		26.3.4 Hybrid Vega Calculations	1105
		26.3.4.1 Definition and Analysis	1105
	00.4	26.3.4.2 Numerical Example	1107
		Skew and Smile Vegas	1107
	26.5	Vegas and Correlations	1109
		26.5.1 Term Correlation Effects	1109
		26.5.2 What Correlations should be Kept Constant?	1110
		26.5.3 Vegas with Fixed Term Correlations	1112
	200	26.5.4 Numerical Example	1113
		Deltas with Backbone	1114
		Vega Projections	1116
	26.8	Some Notes on Computing Model Vegas	1118
A	pper	ndix	
$\mathbf{A}$	Mar	rkovian Projection	1123
	A.1	Marginal Distributions of Ito Processes	1123
	A.2	Approximations for Conditional Expected Values	1128
		A.2.1 Gaussian Approximation	1128
		A.2.2 Least-Squares Projection	1130
	A.3	Applications to Local Stochastic Volatility Models	1131
		A.3.1 Markovian Projection onto an SV Model	1131
		A.3.2 Fitting the Market with an LSV Model	1133
		A.3.3 On Calculating Proxy Local Volatility	1137
	A.4	Basket Options in Local Volatility Models	1139
	A.5	Basket Options in Stochastic Volatility Models	1143
	A.A	Appendix: $E(\sqrt{z_n(t)z_m(t)})$ and $E(\sqrt{z_n(t)})$	1146
		A.A.1 Proof of Proposition A.A.1	1147
		A.A.1.1 Step 1. Reduction to Covariance	1147
		A.A.1.2 Step 2. Linear Approximation	1148
		A.A.1.3 Step 3. Coefficients	1148
		A.A.1.4 Step 4. Order of Approximation	1149
		A.A.2 Proof of Lemma A.A.2	1149