## Index

absorbing boundary, see diffusion, absorbing barrier
accrual factor, see year fraction
ADI, see PDE, ADI scheme
adjusters method, see out-of-model adjustment, adjusters method
affine short rate model, 429-442, 510-518
bond reconstitution formula, 431, 513-515
calibration, 439-441
multi-pass bootstrap, 440
calibration to yield curve, 435-437
characteristic function, 432
European swaption, 437
Fourier integration, 437
Gram-Charlier expansion, 437
extended transform, 431
constant parameters, 432, 434
piecewise constant parameters, 434
Feller condition, 319, 430
importance sampling, 1065
moment-generating function, 432, 437
Monte Carlo, 442
multi-factor, 510-518
bond dynamics, 514
bond reconstitution formula, 513-515
existence and uniqueness, 513
exponential affine, 511
Feller condition, 513
forward rate correlation, 514
forward rate dynamics, 514
regularity issues, 512-513
short rate state dynamics, 512
one-factor, 429-442
PDE, 442
regularity issues, 430
short rate domain, 430
short rate dynamics, 429
short rate state dynamics, 435
swap rate volatility, 438
affine approximation, 438
time averaging, 438
time-dependent, 431
volatility skew range, 431
volatility smile, 430
almost surely, 4
American capped straddle, 936
American swaption, 893-898
accrued current coupon, 893
approximating with Bermudan
swaption, see Bermudan swaption, approximating American swaption
discontinuity of exercise value in time, 893
PDE, 895-897
extra state variable, 896-897
proxy Libor rate method, 895-896
American/Bermudan option, 30-42
Bellman principle, 32, 33, 69
Black-Scholes model, 837
capped, 936
conditional on no exercise, 31
continuation region, 33
discontinuity at expiry, 39
duality, 36
early exercise boundary, 37
early exercise premium, 36, 39, 42
exercise never optimal, 36
exercise policy, 30
exercise region, 33
exercise value, 30
high contact condition, 38
hold value, 32
integral representation, 39, 41
lower bound, see Monte Carlo, lower
bound for American option
marginal exercise value decomposition, 41
Monte Carlo, 158-165
confidence interval for value, 164
random tree, 164
stochastic mesh, 165
PDE jump condition, 34
perfect foresight bias, 160
short-maturity asymptotics, 39
smooth pasting condition, 37,38
supermartingale, 31
upper bound, see Monte Carlo, upper bound for American option
annuity mapping function, see terminal swap rate model, annuity mapping function
annuity measure, see measure, annuity arbitrage opportunity, 8
arbitrage pricing, 11
arithmetic put-call symmetry, 940
Arrow-Debreu security, 21, 76, 78, 79, 456, 460, 1048
backward Kolmogorov equation, 456
forward Kolmogorov equation, 456
art of derivatives trading, 980
Asian option, 70
Black model, 920
Monte Carlo, see Monte Carlo, Asian option
PDE, see PDE, Asian option
ATM backbone, see volatility smile, ATM backbone
autocorrelation, see inter-temporal correlation
averaging, see calibration, time averaging
averaging cash flow, 201, 720-721 convexity adjustment, 720
averaging swap, see averaging cash flow

Bachelier model, see Normal model
backbone, see volatility smile, backbone
backward Kolmogorov equation, see Kolmogorov backward equation
balance-guarantee swap, 898
band swap, see flexi-swap
"bang-bang", 900
barrier option, 44
Broadie adjustment for sampling frequency, see Monte Carlo, sampling extremes, adjusting barrier for sampling frequency
continuous barrier, 64
discrete barrier, 66
importance sampling, 1074-1077
Markovian projection, see Markovian projection, barrier option
Monte Carlo, see Monte Carlo, barrier option
on capped straddle, 937
one-touch, 939
pathwise differentiation method, 1041-1044
recursion, 1043
payoff smoothing, see payoff smoothing, barrier option
PDE jump condition, 66
rebate, 64
semi-static replication, 939
step-down, 64
step-up, 64
tube Monte Carlo, 1025
up-and-out, 44, 64, 66, 124, 126, 1134
basis point, 169
basis risk, see yield curve, basis risk
basket option, 205, 1146
Black model, 922
displaced log-normal approximation, 1147
local volatility model, 1145

## Index xxiii

Monte Carlo, see Monte Carlo, Asian option on basket
slope of volatility smile, 1148
stochastic volatility model, 1149
BDT model, see Black-Derman-Toy model
Bermudan cancelable swap, see Bermudan swaption; cancelable note
Bermudan option, see American/Bermudan option
Bermudan swaption, 207, 873-918
accreting, see Bermudan swaption, non-standard
American, see American swaption
amortizing, see Bermudan swaption, non-standard
approximating American swaption, 894
bullet, see Bermudan swaption, vanilla
carry, 906, 913
impact on exercise decision, 913
control variate, 1090
exercise fee, 897
exercise value, XXXVIII, 208, 873
flexi-swap, see flexi-swap
gamma-theta mismatch, 912
hold value, XXXVIII, 208
lockout, 207, 873
mid-coupon, 895, 897-898
no-call, see Bermudan swaption, lockout
non-standard, 878-898
calibration by payoff matching, 882, 883
calibration by PVBP matching, 882-884
calibration by tenor matching, 881
calibration to basket, 885-887
calibration to representative swaption, 882
calibration to row of European swaptions, 886
Gaussian short rate model, 886
global calibration, 879, 881
Libor market model, 885
local projection method, 879, 881
lower bound, 891, 907

Markov-functional model, 879
quadratic Gaussian model, 886
quasi-Gaussian model, 879, 886, 889
representative swaption for accreting Bermudan, 884
representative swaption for amortizing Bermudan, 883, 884
super-replication, 888-892
upper bound, 889, 890, 907
non-vanilla, see Bermudan swaption, non-standard
PDE jump condition, see American/Bermudan option, PDE jump condition
strike, 873
survival measure, 1047
vanilla, 878
zero-coupon, 892-893
Bermudan swaption calibration
adjusters method, 955
local projection method, 552, 874-878
Gaussian short rate model, 875
non-standard Bermudan, see Bermudan swaption, nonstandard
quadratic Gaussian model, 875
quasi-Gaussian model, 875
smile calibration, 876-878
at-the-money, 876
exercise boundary, 877
strike, 876
Bermudan swaption greeks
pathwise differentiation method, 1044-1050
forward induction, 1049-1050
performance, 1050
survival density, 1048
survival measure, 1047
portfolio replication for hedging, 911
Principal Components Analysis, 911
robust hedging, 910-913
static hedging, 911
Bermudan swaption valuation, 820-871
control variate, 1086
non-linear, 1089
sampled at exercise time, 1087
fast pricing, 914
impact of forward volatilities, 874
impact of inter-temporal correlation, 552, 875
impact of mean reversion, 552, 874
impact of the number of factors, 875
Monte Carlo, 903-910
exercise strategy, 904
explanatory variables, 903
parametric lower bound, 904-910
regression lower bound, 903
Bermudanality, 877
Bessel function of the first kind, 282
Bessel process, 281, 282
best-of option, see MAX-option
best-of-calls option, 780
BGM model, see Libor market model
Black model, XXXVIII, 22, 24, 202, 279, 283
Asian option, see Asian option, Black model
basket option, see basket option, Black model
call option, 24
CMS spread, 774
delta, 350, 696
effects of volatility mis-specification, 987
Fourier integration, 329
gamma-vega, 981
log-likelihood ratio, 1060
moment-generating function, 329
PDE, 25
stochastic interest rates, 28, 30
strike-specific volatility, 696
time-dependent parameters, 27 , 983-985
vega, 696
use in calibration, 702
with dividends, 28
Black shadow rate model, 450
Black-Derman-Toy model, 443-445
mean-fleeting, 445
short rate dynamics, 444
Black-Karasinski model, 445
Black-Scholes model, see Black model
Black-Scholes-Merton model, see Black model
BMA index, 192, 265
BMA rate, 192

Boltzman-Gibbs distribution, see out-of-model adjustment, path re-weighting method, Boltzman-Gibbs distribution
Bond Market Association, see BMA index
box smoothing method, see payoff smoothing, box smoothing
break-even rate, see forward swap rate
Broadie adjustment for sampling frequency of barriers, see Monte Carlo, sampling extremes, adjusting barrier for sampling frequency
Brownian bridge, 125, 645, 646
conditional moments, 129
Libor market model, see Libor market model valuation, Monte Carlo, Brownian bridge
path construction, see Brownian motion, path construction by Brownian bridge
sampling extremes, see Monte Carlo, sampling extremes, with Brownian bridge
Brownian motion, 4
geometric, 16
Haar function decomposition, see Brownian motion, path construction by Brownian bridge
Ito integral, see Ito integral
Karhunen-Loeve decomposition, see Brownian motion, path construction by Principal Components
path construction, 106
path construction by Brownian bridge, 128, 129
path construction by Principal Components, 130
Stratonovich integral, see Stratonovich integral
BSM model, see Black model
$C^{0}$, XXXVIII
$C^{1}$, XXXVIII
$C^{2}$, XXXVIII
$C^{n}$, XXXVIII
calibration, 299

## Index xxv

calibration norm, 628-631
fit, 632
regularity, 632
cold start, 631
forward induction, 443, 456, 953
Levenberg-Marquardt, 631
local projection method, see local projection method
Markovian projection method, see Markovian projection
most likely path, 990
stochastic optimization method, 953
time averaging, 301, 307, 363, 370-381, 548, 581, 666
algorithm, 376-381
non-zero correlation, 376
skew, 373-374
volatility, 371-373
volatility of variance, 374-376
callable Libor exotic, see CLE
callable zero, see Bermudan swaption, zero-coupon
cancelable note, 214, 827, 828
ATM, 858
carry, 856, 913
cancelable swap, see cancelable note
cap, 186, 202
caplet volatility from cap volatility, 704
interpolation, 705
precision norm, 705
relaxation, 706
smoothness norm, 706
splitting scheme, 706
digital, 203, 209
valuation formula, 202
Capital Asset Pricing Model, 357
capped floater, 209
Cauchy distribution, 98, 101
Monte Carlo, 98
certificate of deposit, 194
CEV model, 280-286
attainability of zero, 280
displaced, 285
European call option value, 282, 283
explosion, 280
regularization, 284
relation to Bessel process, 281
strict supermartingale, 280
time-dependent, 304
effective parameter, 305
volatility skew, 284
characteristic function, 20
Cheyette model, see quasi-Gaussian model
chi-square distribution, 100
Monte Carlo, 100, 102
non-central, see non-central chi-square distribution
PDF, 100
chooser cap, see flexi-cap
chooser swap, see flexi-swap
CIR model, see Cox-Ingersol-Ross model
CLE, 213, 216, 626, 815-871, 873
accreting at coupon rate, 216, 868
carry, 857, 906, 913
impact on exercise decision, 847, 857
definition, 820
exercise value, XXXVIII, 215, 820
hold value, XXXVIII, 215, 820, 821
lockout, 213
marginal exercise value decomposition, 822
multi-tranche, 217
no-call, see CLE, lockout
optimal exercise, 822
single-rate, 862
smooth function of Monte Carlo path, 1029
snowball, 216, 870
CLE calibration, 815-820
local projection method, 862-868
calibration targets, 863
core swap rate analog, 865
local models, 864-865
quadratic Gaussian model, 865
quasi-Gaussian model, 864
two-factor Gaussian model, 864
two-strike calibration, 865
vega, 867
low-dimensional models, 862-868
model choice, 819
single-rate, 862-863
to forward volatility, 819
CLE greeks, 1036-1040
as sum of coupon greeks, 1037

## xxvi Index

discontinuity in Monte Carlo, 1041
freezing exercise boundary, 833 , 1039, 1040
freezing exercise time, 1038-1040
likelihood ratio method, see likelihood ratio method
pathwise differentiation method, 1035-1040, 1058-1060
computational complexity, 1052
forward induction, 1049-1050
survival density, 1048
survival measure, 1047
perturbation method, 1040, 1059
computational complexity, 1053
portfolio replication for hedging, 911
recursion, 1036
source of noise, 1040
tube Monte Carlo, 1029
CLE regression, 823-862
automatic selection of regression variables, 855
boundary optimization, 831
cancelable note, 827-828
choice of regression variables, 848-854
decision only, 828-830
discrepancy principle, 859
excluding suboptimal points, 856
exercise value, 825-827
explanatory variables, 850-854
classification, 851
CMS spread, 851
core swap rate, 851
stochastic volatility, 854
with convexity, 852-854
general-to-specific approach, 856
generalized cross-validation, 859
L-curve method, 859
Libor market model, 849, 850
state variables, 849
lower bound, 831-833
perfect foresight bias, 832
pseudo-inverse method, 860
quadratic Gaussian model, 849
quasi-Gaussian model, 849
regression operator, 824
regression variables, 823
rescaling, 861
reuse exercise boundary, see CLE greeks, freezing exercise boundary
ridge regression, see CLE regression, Tikhonov regularization robust implementation, 858-862
singular value decomposition, 104 stabilization, 859
state variables, 848-849
Libor market model, 849
SVD decomposition, 860, 861
connection to Tikhonov regularization, 861
Tikhonov regularization, 162, 255, 859-861
connection to SVD, 861
truncated SVD decomposition, 162, 860, 861
two-step, 857
upper bound, 837-848
alternative methods, 847
computational cost, 841
improvements to algorithm, 845-847
nested simulation algorithm, 837-847
non-analytic exercise values, 843-845
simulation within a simulation, see CLE regression, upper bound, nested simulation algorithm
CLE valuation, 215, 820-871
as cancelable note, 827
boundary optimization, 831
confidence interval for value, 842
control variate, see Bermudan swaption valuation, control variate
discontinuous function of Monte Carlo path, 1041
duality, 836, 1093
multiplicative, 1093
duality gap, 839, 842, 908, 909
in stochastic volatility models, 910
exercise policy consistency conditions, 833
fast pricing, 916
Hamilton-Jacobi-Bellman equation, 821

## Index xxvii

impact of forward volatility, 818
impact of inter-temporal correlation, 863
impact of volatility smile dynamics, 819
Libor market model, 824
lower bound, $834,841,845,848$
by regression, see CLE regression, lower bound
iterative improvement, 833
iterative improvement by nested simulation, 835
quality test, 1060
LS method, see CLE regression
Monte Carlo, 823-862, 903
optimal exercise policy, 833, 835, 1039
PDE, 868-871
accreting at coupon rate, 868
path-dependent, 868-871
similarity reduction, 869
snowball, 870
perfect foresight bias, 832
policy fixing, 846
recursion, 821
regression method, see CLE regression
tube Monte Carlo, 1029
upper bound, 836-848
cancelable note, 844
nested simulation algorithm, 839, 908
non-analytic exercise values, 843-845
weighted coupon decomposition, 916
CMS, 206
annuity to forward measure change, 734-737
convexity adjustment, 721-744
annuity mapping function, see terminal swap rate model, annuity mapping function
correcting arbitrage, 732-733
density integration method, 736
impact of mean reversion, 733-734
impact of volatility smile, 733
impact on implied volatility, 774
Libor market model, 729-731
linear TSR model, 726-728
out-of-model adjustment, 963, 964
quasi-Gaussian model, 728-729
replication method, 722-724
stochastic volatility model, 738
swap-yield TSR model, 726
vega hedging, see terminal swap rate model, linear TSR model, vega hedging
hedging portfolio, 723
quanto, see quanto CMS
CMS cap, 207, 695
impact of CMS convexity on volatility smile, 739
link to European swaptions, 739
CMS digital spread option, 789
dimensionality reduction, 789
CMS floor, 207
CMS rate, 206
distribution in forward measure, 734-737
CMS spread option, 210, 211, 619, 688, 763, 774
by integration, 775
copula method, 774-782
dimensionality reduction, 787
floating digital, 790
Gaussian copula, 775
correlation impact, 776
vega to swaptions, 776
implied copula, 779
implied correlation, 776
Libor market model, 617-619, 634, 690, 806
closed-form approximation, 808
Libor market model calibration, 634
local volatility model, 1145
Margrabe formula, 810
Markovian projection, 1145, 1149
multi-stochastic volatility, see multi-stochastic volatility model
non-standard gearing, 775, 789
dimensionality reduction, 789
Normal spread volatility, 774
one-dimensional integration, 787
out-of-model adjustment, 964, 966
power Gaussian copula, 779
quadratic Gaussian model, 808
closed-form approximations, 808

## xxviii Index

risk management with one-factor model, 971
stochastic volatility
correlation impact, 805
stochastic volatility de-correlation, 962
stochastic volatility model, 1149
correlation impact, 803
vega in Libor market model, 1116
CMS swap, 206, 695
valuation formula, 207
CMS-linked cash flow, 721-744
direct integration method, 734
replication method, 723
coherent risk measure, see risk measure, coherent
collateral, 192, 266
complementary Gamma function, 281
complete market, 11
compounded rate, 200
conditional expected value, 19
iterated conditional expectations, see iterated conditional expectations
projection approximation, see Markovian projection, conditional expected value by projection
constant elasticity of variance model, see CEV model
constant maturity swap, see CMS swap
contingent claim, see derivative security
continuity correction, see payoff smoothing, continuity correction
control variate, 146-149, 330, 652, 653, 1077-1094
adjusters method, 955
construction from MC upper bound, 1093
dynamic, 148, 653, 1090-1093
regression-based, 1091
efficiency, 147
impact on risk stability, 1093
instrument-based, 1086-1090
model-based, 675, 1077-1086
non-linear controls, 147-149
path re-weighting method, 961
proxy Markov LM model, 1078
proxy model, see control variate, model-based
convexity adjustment
averaging swap, see Libor-with-delay, convexity adjustment
CMS, see CMS, convexity adjustment
futures, see ED future, convexity adjustment
Libor-in-arrears, see Libor-inarrears, convexity adjustment
Libor-with-delay, see Libor-withdelay, convexity adjustment
moment explosion, 759-762
second moment, 759
copula, 768
Archimedean, 770
Monte Carlo, 798
Clayton, 770
conditional CDF, 790
Frechet bounds, 769
Gaussian, 766
CMS spread option, see CMS spread option, Gaussian copula integration, 787
joint CDF, 767
joint PDF, 767, 775
mixture, 772
Monte Carlo, 797
Gumbel, 770, 771
implied, 779
independence, 768
mixture, 772
Monte Carlo, 798
perfect anti-dependence, 769
perfect dependence, 768
power Gaussian, 773, 778 parameter impact, 779
product, 773
Monte Carlo, 798
reflection, 771
Monte Carlo, 798
Sklar's theorem, 769
copula density, 770
copula method, 766
CMS spread option, see CMS spread option, copula method
dimensionality reduction, 787-796
by conditioning, 791-795

## Index xxix

by measure change, 795-796
forward swaption straddle, 949
integration, 784-796
inverse CDF caching, 785
singularities, 786
limitations, 799-800
mapping function, 793
Monte Carlo, 797-799
observation lag, 782
quanto options, 747
volatility swap, 934
core correlations, see inter-temporal correlation
core volatilities, 863, 874
correlation extractor, see Libor market model, correlation extractor
correlation risk sensitivity, 1119
correlation smile, 776
Cox-Ingersol-Ross model, 430
multi-factor, 518
two-factor, 516
Crank-Nicolson scheme, see PDE, Crank-Nicolson scheme
credit risk, 260, 975
credit value adjustment, 266, 914
cross-currency basis swap, see floatingfloating cross-currency basis swap
cross-currency basis swap spread, 262, 265
CRX basis swap, see floating-floating cross-currency basis swap
CRX spread, see cross-currency basis swap spread
cumulant-generating function, 154
curve cap, 211, 764
range accrual, see range accrual, curve cap
CVA, see credit value adjustment
date rolling convention, 224
day count convention, 223-226
30/360, 225
Actual/360, 224
Actual/365.25, 224
day count fraction, see year fraction
deflator, 9
delta, 18, 132, 355, 980
bucketed interest rate deltas, 251, 1045
forward rate, 253
Jacobian method, see risk sensitivities, Jacobian method
par-point, 251, 252, 256, 257, 993
parallel, 257
with backbone, 1120-1122
delta hedge, 18
density process, 9
derivative security, 11
attainable, 11
pricing, 11
diffusion, 4, 15
absorbing barrier, 281, 289
displaced, 285
Feller boundary classification, 280
Feller condition, 319
Fubini's theorem, 407
integration by parts, 120
Ito integral, see Ito integral
Ito process, 4
local time, 26, 294
Ornstein-Uhlenbeck process, 411
polynomial growth condition, 19
predictable process, 7
scale measure, 280
SDE, 15
generator, 19
linear, 16
locally deterministic, 172,539
strong Markov, 15
strong solution, 15
weak solution, 15
speed measure, 280
diffusion invariance principle, 14
discount bond, XXXVIII, 23, 167
valuation formula, 172
discount curve, see yield curve
displaced CEV model, see CEV model, displaced
displaced log-normal model, 285
basket option, 1147
canonical form, 286
explicit solution to SDE, 312
Fourier integration, 328
implied correlation, 809
moment matching, 920
moment-generating function, 329
time-dependent, 304
effective skew, 305
explicit solution to SDE, 307
range for process, 306
Dupire local volatility, 1131
proof by Tanaka extension, 294, 1131
duration, 246
DVF model, see local volatility model
Dybvig parameterization, see short rate model, Dybvig parameterization
early exercise, 30
ED future, 168-170, 196-197, 695, 748-759
convexity adjustment, 187, 197, 748-759
from market inputs, 751
Gaussian HJM model, 186
impact of volatility smile, 750,756
Libor market model, 751, 756
replication method, 751, 755
delivery arbitrage, 170
futures rate, 169
definition, 196
instantaneous, 170, 172, 173
martingale in risk-neutral measure, 172, 749
martingale in spot Libor measure, 749
simple, 169
to forward rate, 754,758
mark to market, 169
yield curve construction, 231, 992
ED futures contract, see ED future
effective volatility
local volatility model, see local volatility model, effective volatility
stochastic volatility model, see stochastic volatility model, effective volatility
envelope theorem, 1038
Eonia, 193, 200
equivalent martingale measure, see measure, equivalent martingale
Esscher transform, see exponential twisting

Eurodollar futures contract, see ED future
European call option, 24
at-the-money, 24
Fourier integration, 324
in-the-money, 24
out-of-the-money, 24
probability density from, see volatility smile, probability density from
European digital call option, 60
European option
Fourier integration, 326
European put option, 24
at-the-money, 24
in-the-money, 24
out-of-the-money, 24
European swaption, 203, 695-703
cash-settled, 205, 742-744
payoff, 743
put-call parity, 743
replication method, 742, 743
core swaptions, 422, 817
coterminal swaptions, see European swaption, core swaptions
diagonal swaptions, see European swaption, core swaptions
forward swaption straddle, see forward swaption straddle, 943
midcurve, 223
non-standard, see Bermudan swaption, non-standard
Black formula, 887
physically-settled, 205
SV model calibration, 701-702
swap-settled, 205, 743
swaption grid, 205, 701
swaption strip, 421
tenor, 204
valuation formula, 204
volatility cube, 696
European-style option, 95
replication method, 337
valuation by volatility mixing, 339
exchange market, 193
Chicago Mercantile Exchange, 196
London International Financial Futures and Options Exchange, 196

## Index xxxi

Marchè à Terme International de France, 196
exotic swap, 205, 208, 209, 820, 951
CMS spread, 764
CMS-based, 210
digital CMS spread, 764
global cap, 219
global floor, 219
knock-out, 218
Libor-based, 209
multi-rate, 210, 764
path-dependent, 212
principal amount, 208
range accrual, see range accrual
snowball, 212
spread-based, 210
structured coupon, 208-211
expectations hypothesis, 173
expected hedging P\&L, 988
exponential distribution, 98
Monte Carlo, 98
exponential integral, 334
exponential twisting, 154
extra state variable method, see PDE, path-dependent options
"The Fed Experiment", 450
Federal funds future, 201
Federal funds rate, 192, 200, 201, 266
effective, 192
target, 192
Federal funds/Libor basis swap, 201, 266
Feller condition, see diffusion, Feller condition
Feynman-Kac solution, 21
FFT, see stochastic volatility model, Fourier integration
filtration, 3,4
usual condition, 3
flexi-cap, 71
flexi-swap, 898-903
decomposition into Bermudan swaptions, 899
local projection method, 899
marginal exercise value decomposition, 901
narrow band limit, 902
PDE, 899, 901
purely local bounds, 899
"flip-flop", 210
floating digital, 790, 792
dimensionality reduction, 790
floating digital spread option, 790
dimensionality reduction, 790
floating-floating cross-currency basis swap, 262, 264, 265
floating-floating single-currency basis swap, 201, 268
floor, see cap
Fokker-Plank equation, see Kolmogorov forward equation
Fong-Vasicek model, 452-453, 515
bond reconstitution formula, 452
forward CMS straddle, 941, 944, 945
swaption, see forward swaption straddle
volatility, see forward volatility
forward contract, 195
forward Kolmogorov equation, see Kolmogorov forward equation
forward Libor model, see Libor market model
forward Libor rate, XXXVIII, 168, 191, 192, 196
accrual end date, 224
accrual period, 224
accrual start date, 224
martingale in forward measure, 174
tenor, 168
variance by replication method, 756
year fraction, see year fraction
forward par rate, see forward swap rate
forward price, 24, 168
forward rate, 167
continuously compounded, XXXVIII, 168
instantaneous, XXXVIII, 169
simple, 168
tenor, 168
volatility hump, 416, 492
forward rate agreement, see forward contract
forward starting option, 222
forward swap rate, XXXVIII, 171, 199

## xxxii Index

distribution in forward measure, see CMS rate, distribution in forward measure
expiry, 171
fixing date, 171
linking forward and annuity measure, 735
market-implied variance, 555
martingale in swap measure, 178
non-standard, 879
decomposition, 880
tenor, 171
weighted average of Libor rates, 171, 256
forward swaption straddle, 223, 945-950
copula method, 949
relation to CMS spread option, 948
triangulation, see forward volatility, triangulation
vanilla model, 946
vega exposure, 948
volatility, see forward volatility
forward volatility, 222
connection to inter-temporal correlations, see inter-temporal correlation, connection to forward volatilities
hedging, 912
impact of rate correlation, 918
impact of volatility smile, 945
Libor rate, see volatility, forward volatility of Libor rate
triangulation, 948
forward volatility derivative, 220, 222
forward swaption straddle, see forward swaption straddle
implied Normal volatility contract, 223
midcurve swaption, see European swaption, midcurve
volatility swap, see volatility swap
forward yield, see forward rate
Fourier transform, 325
inverse, 325
FRA, see forward contract
Frobenius norm, see matrix, Frobenius norm
fundamental matrix, 484
fundamental theorem of arbitrage, 10
fundamental theorem of derivatives trading, 987
futures contract, see ED future
futures rate, see ED future, futures rate
fuzzy logic, see payoff smoothing, fuzzy logic
FX rate, 179, 745, 746
dynamics in domestic risk-neutral measure, 180
forward, 178
martingale in domestic forward measure, 180

Gâteaux derivative, 253
gamma, 980
pathwise differentiation method, see pathwise differentiation method, gamma
payoff smoothing, 1019
relationship to vega, 981
gamma distribution, 100
Monte Carlo, 100, 102
PDF, 100
Gamma function, XXXVII
incomplete, see incomplete Gamma function
quick approximation, 1153
Gauss-Hermite quadrature, see quadrature, Gauss-Hermite
Gaussian copula, see copula, Gaussian
Gaussian distribution, XXXVII
conditional distribution, 646
cumulant-generating function, 154
imaginary mean, 796
inverse CDF, 99, 165
linear transform, 103
measure change, 795
multi-dimensional PDF, 103
quadratic form, 522
moment-generating function, 522 , 533
moments, 534
Gaussian HJM model, 184-187
caplet, 186
ED future convexity adjustment, see ED future, convexity adjustment, Gaussian HJM model

## Index xxxiii

time-stationary, 416
zero-coupon bond option, 185
Gaussian multi-factor short rate model, see Gaussian short rate model, multi-factor
Gaussian one-factor short rate model, see Gaussian short rate model
Gaussian short rate model, 406, 413-429, 478-510
as special case of affine model, 430
Bermudan swaption, see Bermudan swaption calibration, local projection method, Gaussian short rate model
bond dynamics, 415
bond reconstitution formula, 414
efficient calculation, 415
calibration, 421
bootstrap, 422
calibration to yield curve, 414
European swaption, 418, 421
Jamshidian decomposition, 418
fast pricing of Bermudan swaptions, 914
forward rate dynamics, 413
forward rate volatility, 413
dynamics, 417
humped volatility structure, 416
in spot measure, 428
in terminal measure, 428
mean reversion, see mean reversion
mean reversion calibration, see mean reversion calibration
Monte Carlo, 425-429
approximate, 427
Euler scheme, 427
exact, 425
other measures, 428
multi-factor, 478-510
benchmark rate parameterization, 506-508
benchmark rates, 506
benchmark tenors, 506
bond reconstitution formula, 478, 481, 483
bond volatility, 479
calibration, 506
classic development, 485-488
correlated Brownian motions, 489
correlation stationarity, 488
European swaption, 500-505
European swaption by Jamshidian decomposition, 503
factors and loadings, see Gaussian short rate model, multi-factor, statistical approach
forward rate correlation, 488-489
forward rate volatility, 482
Gaussian swap rate approximation, 504-505
loadings, 499
mean reversion matrix diagonalization, 487-488
Monte Carlo, 508-509
PDE, 510
rotations, 484
separability, 478-485
short rate dynamics, 479
short rate state distribution, 485, 509
short rate state dynamics, 479-485
short rate state dynamics, integrated, 485, 509
single Brownian motion, 496
statistical approach, 495-500
swap rate volatility, 505
PDE, 423-425
boundary conditions from PDE, 424
short rate distribution, 426
short rate dynamics, 413
short rate state dynamics, 414, 425
integrated, 425
swap rate dynamics in annuity measure, 420
swap rate volatility, 420
time-stationary, 416
two-factor, 489-495
bond reconstitution formula, 490, 500
CLE, see CLE calibration, local projection method, two-factor Gaussian model
correlated Brownian motions, 490
correlation stationarity, 491
doubly mean-reverting form, 493
European swaption by Jamshidian decomposition, 500-504
forward rate correlation, 490-491
forward rate dynamics, 490
forward rate volatility, 490-491, 493, 494
short rate state conditional distribution, 502
short rate state correlation, 490
short rate state dynamics, 490
single Brownian motion, 495 volatility hump, 492-493
Gaussian two-factor short rate model, see Gaussian short rate model, two-factor
generalized trigger product, 1074
importance sampling, 1074-1077
pathwise differentiation method, 1041-1044
payoff smoothing, 1074-1077
trigger variable, 1074
tube Monte Carlo, see barrier option, tube Monte Carlo
Girsanov's theorem, 12, 13
Gaussian distribution, 795
Gram-Charlier expansion, 368, 437
greeks, see risk sensitivities
Green's function, 20
grid shifting, see payoff smoothing, grid shifting
GSR model, see Gaussian short rate model
Gyöngy theorem, see Markovian projection, Gyöngy theorem
$H^{2}, 5$
Hagan and Woodward parameterization, see short rate model, Hagan and Woodward parameterization
hat smoothing method, see payoff smoothing, hat smoothing
Heath-Jarrow-Morton model, see HJM model
hedge, 251
best hedging strategy, 355
beta, 357
minimum variance, 355-357
model-independent, 716
semi-static, see replication method, semi-static
shadow delta, see volatility smile, shadow delta hedging
sub-replicate, 717
super-replicate, 717, 979
zero-beta, 357
Hermite matrix, 270
Heston model, see stochastic volatility model
HJM model, 181-189
bond dynamics, 181
forward bond dynamics, 182
forward rate dynamics, 182
Gaussian, see Gaussian HJM model
Gaussian Markov, 187-189
short rate dynamics, 188
log-normal, 189
Markovian, 405
separable, 413
short rate dynamics, 183
stochastic basis, see HJM model, two-curve
two-curve, 678-681
forward rate spread dynamics, 679
Gaussian basis spread, 681
index bond dynamics, 680
index forward rate dynamics, 680
index short rate dynamics, 680
quanto correction, 681
Ho-Lee model, 406-410
bond dynamics, 409
bond reconstitution formula, 408
calibration to yield curve, 407
drawbacks, 410
forward rate dynamics, 409
short rate dynamics, 408
hybrid differentiation method, 1061
implied volatility, see volatility, implied
importance sampling, 146, 149-158, 1063-1077
application to payoff smoothing, 1067
barrier option, see barrier option, importance sampling
density formulation, 149
efficiency, 151

## Index xxxv

generalized trigger product, see generalized trigger product, importance sampling
least-squares, 154
likelihood ratio, 150, 153, 155
rare events, 154
approximately optimal mean shift in multi-variate case, 158
asymptotic optimality, 158
efficiency, 156
minimal variance, 155
multi-variate, 156
SDE, 151-154
short rate model, see short rate model, importance sampling
survival measure, 1067
simulation under, 1072, 1074, 1076
TARN, see TARN, importance sampling
incomplete Gamma function, XXXVII, 281
index, 206
index option, see basket option
infinitesimal operator of SDE, see diffusion, SDE, generator
infinitesimal perturbation analysis, 136
information theory, 957
instantaneous futures rate, see ED future, futures rate, instantaneous
integration by parts for diffusion process, see diffusion, integration by parts
inter-temporal correlation, 422, 552, 818, 863, 874
connection to forward volatilities, 818
hedging, 875, 912
impact of mean reversion, 552
impact of volatility smile, 945
impact on Bermudan swaption, see Bermudan swaption valuation, impact of inter-temporal correlation
impact on CLEs, see CLE valuation, impact of inter-temporal correlation
impact on TARNs, 929
mean reversion calibration to, see mean reversion calibration, to inter-temporal correlations interbank money market, 192
International Swaps and Derivatives Association, 192, 266
intrinsic value, 27
inverse floater, 209
iterated conditional expectations, 176
Ito integral, 4, 5
Ito isometry, 5
Ito's lemma, 6
Ito-Taylor expansion, 118
Jacobian, see risk sensitivities, Jacobian method
Jamshidian decomposition
American/Bermudan option, see American/Bermudan option, Jamshidian decomposition
European swaption, see Gaussian short rate model, European swaption, Jamshidian decomposition

Kolmogorov backward equation, 19, 20
Kolmogorov forward equation, 20, 386, 457, 1048
correct boundary conditions, 386
discrete consistency with backward equation, 458
Kullback-Leibler relative entropy, 957
kurtosis, 375
$L^{1}$, XXXVIII, 4
$L^{2}$, XXXVIII, 4
ladder, 985
ladder swap, see ratchet swap
Lagrange basis functions, see PDE, Lagrange basis; payoff smoothing, Lagrange basis
Lagrange multiplier, 249, 958
least squares method, see CLE regression
LIA, see Libor-in-arrears
Libor curve, see yield curve
Libor market model, 449, 589-692, 729, 866, 910
annuity mapping function, 730, 731
asset-based adjustment, 963
xxxvi Index
back stub, 655-660
arbitrage-free, 657-659
from Gaussian model, 659-660
simple, 656-657
choosing number of factors, 612
CLE, 819
CMS convexity adjustment, 964
correlation extractor, 863
deflated bond dynamics, 649
delta with backbone, 1120-1122
drift approximation, 644
Brownian bridge, 1079
drift freezing, 1052
exercise boundary, 910
exercise strategy, 907
expected value of Libor rate in annuity measure, 669
front stub, 660-666
exogenous volatility, 661-664
from Gaussian model, 665-666
simple interpolation, 664-665
zero volatility, 660-661
in hybrid measure, 640
index function, see tenor structure, index function
Libor rate correlation, 601-612, 757
correlation PCA, 609
covariance PCA, 624
historical estimation, 604
majorization, 611
parametric form, 606, 607
PCA, 602-604
poor man's correlation PCA, 612
regularization, 608
Libor rate dynamics, 591-601
annuity measure, 731
in forward measures, 592-593
in hybrid measure, 595
in spot measure, 594
in terminal measure, 594, 639
Libor rate inter-temporal correlation, 757
Libor rate volatility
from volatility norm, 623-625
functional form, 620
grid-based, 620-621
interpolation, 622-623
Libor rate volatility link to HJM forward rate volatility, 596
link to HJM, 595
local volatility, 596-598
CEV, 597
displaced log-normal, 597
existence and uniqueness, 597, 598
LCEV, 597
log-normal, 597
Markov, 674-675, 1078-1086
as control variate, 1084
Brownian bridge, 1079
calibration, 1082
one-factor, 1079
one-factor reconstitution formula, 1080
separable volatility, 1080
two-factor, 1081
two-factor reconstitution formula, 1081
Markovian projection, 666, 668, 1139
model risk, 627
multi-stochastic volatility, 688-692, 962
caplet, 690
CMS spread option, 690
European swaption, 690
moment-generating function, 690
Musiela parameterization, 602
pathwise derivative
forward Libor rate, 1051
forward swap rate, 1055
numeraire, 1054
structured coupon, 1055 stub bond, 1054
pathwise differentiation method, 1051-1058
computational complexity, 1052
PCA, see Principal Components Analysis
portfolio replication, 912
stochastic basis, see Libor market model, two-curve
stochastic variance dynamics, 688
stochastic volatility, 599-601
moment-generating function, 687
non-zero correlation, 686
stub volatility, 662,666
swap rate correlation, 618-619
swap rate dynamics, 615,667
approximate, 616
time-stationary, 621
tool to extract forward volatility, 819
two-curve, 682-686
deterministic spread, 685
European swaption, 684
Libor rate dynamics, 683
Monte Carlo, 684
swap rate dynamics, 684
vega, see vega, Libor market model
Libor market model calibration, 620-635
algorithm, 631, 634, 674
bootstrap, 633
for vega, 1111
cascade, see Libor market model calibration, bootstrap
choice of instruments, 625
effective skew, 670
effective volatility, 669
global, 626
grid-based, see Libor market model
calibration, global
local, 626
objective function, 628
PCA, 624
row-by-row, 631, 632
to spread options, 633, 806
volatility skew, 635
volatility smile, 672
Libor market model valuation
Bermudan swaption, see Bermudan swaption valuation, Monte Carlo
caplet, 613
CLE, see CLE valuation, Libor market model
CMS convexity adjustment, see CMS, convexity adjustment, Libor market model
CMS spread option, see CMS spread option, Libor market model
curve interpolation, 655-666
European swaption, 614, 616, 666
Libor-with-delay, see Libor-withdelay, Libor market model
Monte Carlo, 635
analysis of computational effort, 637
antithetic variates, 652
Brownian bridge, 645
choice of numeraire, 640
control variate, 652
discretization bias, 637
Euler scheme, 636
front stub, 662
high-order schemes, 648
importance sampling, 653
lagging predictor-corrector, 642
large time steps, 639, 644-647
log-Euler scheme, 636
martingale discretization, 648-651
Milstein scheme, 648
predictor-corrector, 641, 642, 645, 651
survival measure, 1072, 1075
two-curve, 684
variance reduction, 651-653
multi-rate vanilla derivative, 806
PDE, see Libor market model, Markov
TARN, see TARN, Libor market model
volatility swap, see volatility swap,
Libor market model
Libor rate, see forward Libor rate
Libor-in-arrears, 200, 714-717
convexity adjustment, 715
replication method, 716
sub-replicating portfolio, 717
super-replicating portfolio, 717
Libor-with-delay, 717-721
convexity adjustment, 718
Libor market model, 718, 720
quasi-Gaussian model, 718, 719
replication method, 718, 720
swap-yield TSR model, 718
likelihood ratio method, 139-142, 1060-1061
discontinuous payoff, 138
exploding variance, 1061
for Euler scheme, 141-142
for Milstein scheme, 142
log-likelihood ratio, 140
score function, 140
vega, 1124
linear regression, 146
Lipschitz function, 137
xxxviii Index
LM model, see Libor market model
local projection method, 558, 862, 863, 953, 1097
Bermudan swaption, see Bermudan swaption calibration, local projection method
CLE, see CLE calibration, local projection method
non-standard Bermudan swaption, see Bermudan swaption, non-standard, local projection method
TARN, see TARN, local projection method
volatility swap, see volatility swap, local projection method
local stochastic volatility model, 316, 1137-1145
calibration, see Markovian projection, LSV calibration
Markovian projection, see Markovian projection, LSV calibration
local time, see diffusion, local time
local volatility model, 277-312
approximation with displaced log-normal model, 286
asymptotic expansion, 295-299
basket option, see Markovian projection, basket option in LV model
CEV, see CEV model
displaced log-normal, see displaced log-normal model
effective convexity, 307-312
effective skew, 301-312
effective volatility, 301
expansion around displaced log-normal model, 296
expansion around Gaussian model, 298
forward equation for call options, 293
PDE, 292-295
simultaneous for multiple parameters, 293
space discretization, 292
transform to constant diffusion coefficient, 88, 292
quadratic volatility, see quadratic volatility model
range-bound, 287
small-noise expansion, see volatility, small-noise expansion
smile dynamics, 279, 350, 352
time-dependent, 299-312 separable, 300
log-normal distribution, XXXVII, 16
moment matching, see moment matching
moments, 16
Monte Carlo, 101
Longstaff-Schwartz method, see CLE regression
Longstaff-Schwartz model, 516-517
bond reconstitution formula, 516
lookback option, 124
Monte Carlo, see Monte Carlo, lookback option
LS method, see CLE regression
LSV model, see local stochastic volatility model
LVF model, see local volatility model
Malliavin calculus, 142, 1042, 1060
Margrabe formula for spread option, 810
mark-to-model, 816
Markov process, 15
Feynman-Kac theorem, see Feynman-Kac solution
strong, 15
transition density, 20
Markov-functional model, 470-476
calibration to yield curve, 473
criticism, 476
Libor parameterization, 471
log-normal, 472
no-arbitrage condition, 471
non-standard Bermudan swaption, 879
numeraire, 470
numeraire mapping, 470
Libor parameterization, 471
non-parametric, 474
swap parameterization, 474
PDE, 475
state process, 470

## Index xxxix

swap parameterization, 473
transition density, 470
Markovian projection, 803, 1129-1156
average option, 1133
barrier option, 1134
basket option in LV model, 1145-1148
basket option in SV model, 1149-1152
CMS spread option, 1145
conditional expected value by
Gaussian approximation, 1134-1135
conditional expected value by projection, 725, 1136-1137
displaced Heston model, 1149, 1151 non-perturbative approximation, 1151
displaced log-normal model, 1136, 1146
Gyöngy theorem, 1130
LSV calibration, 1139-1145
mapping function, 1142
proxy model, 1143-1145
quadratic volatility model, 1137, 1148
quasi-Gaussian model, see quasiGaussian model, Markovian projection
spread option, 1151
stochastic volatility model, 1138
martingale, 5
Doob-Meyer decomposition, 35
exponential, 12
Doleans exponential, XXXVII, 12
local, 5
bounded, 288
martingale representation theorem, 6
Novikov condition, 12
optional sampling theorem, 35
Snell envelope, 31, 821
square-integrable, 5
stopping time, see stopping time
submartingale, 5
supermartingale, 5, 360
CEV, see CEV model, strict supermartingale
quadratic volatility, see quadratic volatility model, strict supermartingale
SV model, see SV model with general variance process, strict supermartingale
matrix
exponential, 484
Frobenius norm, 105, 608, 609, 624, 625,849
infinity norm, 53
positive semi-definite, 103
Cholesky decomposition, 103
rank-deficient, 106
spectral norm, 53
stiffness, 1111
tri-diagonal, 47
MAX-option, 906
mean reversion, 316, 411, 550, 571
effects, 550-552
inter-temporal correlation, 552
swaption volatility ratio, 551
mean reversion calibration, 550-558, 571
to inter-temporal correlations, 555-557
to row of European swaptions, 553, 886
to volatility ratios, 552-555
mean-reverting square-root process, see square-root process
measure, XXXVII
absolutely continuous, 1067
annuity, 178,204
change of numeraire, see numeraire, change of numeraire
domestic, 744
equivalent, 9,1067
equivalent martingale, $8,9,14,171$
foreign, 744
hybrid, 176
local martingale, 10
risk-neutral, XXXVII, 23, 172
domestic and foreign, 179, 180
spot, XXXVII, 175
survival density, 1047
survival for Bermudan swaption, see Bermudan swaption, survival measure
survival in importance sampling, see importance sampling, survival measure
T-forward, XXXVII, 29, 174
domestic and foreign, 180
terminal, 176
min-max volatility swap, 222, 938
capped, 940
semi-static replication, 939
moment explosion, 323, 343, 344, 361, 759, 760
impact on convexity adjustment, see convexity adjustment, moment explosion
SABR model, see SABR model, moment explosion
stochastic volatility model, see stochastic volatility model, moment explosion
SV model with general variance process, see SV model with general variance process, moment explosion
moment matching, 887, 919-923
Asian option, 920
basket option, 922
moment-generating function, 13
Monte Carlo, 95-165
A-stable scheme, 110
Asian option, 107
Asian option on basket, 107
average rate option, see Monte Carlo, Asian option
barrier option, 124-128
adjusting barrier for sampling frequency, 128
double-barrier knock-out, 124
bias, 122
bias/standard error trade-off, 123
Brownian motion, see Brownian motion
calibration by stochastic optimization method, 953
central limit theorem, 96
convergence rate, 97
discretization bias, 426
efficiency, 144
Euler scheme, 110, 111
linear SDE, 112
region of stability, 111
weak convergence order, 111
Euler-Maruyama scheme, see Monte
Carlo, Euler scheme
Heun scheme, 116
higher-order schemes, 116
implicit Euler scheme, 113
region of stability, 114
implicit Milstein scheme, 390
log-Euler scheme, 112, 113
lookback option, 125
low-discrepancy sequence, see Monte Carlo, random number generation, quasi-random
lower bound for American option, 34, 35, 164
parametric, 159, 161
regression-based, 161
mean-square error, 123
Milstein scheme, 119, 121
multi-dimensional, 121
modified trapezoidal scheme, see Monte Carlo, Heun scheme
optimal root-mean-square error, 123
perfect foresight bias, see American/Bermudan option, perfect foresight bias
predictor-corrector, 115, 116
convergence order, 116
random number generation, 97
acceptance-rejection method, 99-101
Box-Muller method for Gaussian distribution, 99
composition method, 101-102
conditional Gaussian, 1066
correlated Gaussian, 103
correlated Gaussian by Cholesky decomposition, 103
correlated Gaussian by eigenvalue decomposition, 104
inverse transform method, 98
linear congruential generator, 97
Marsaglia polar method for
Gaussian distribution, 99
Mersenne twister, 98
period, 98
pseudo-random, 97, 130
quasi-random, 129

Sobol, 129
region of stability, 110
Richardson extrapolation, 122, 468
sample mean, 96
sampling extremes, 124-128
adjusting barrier for sampling
frequency, 128, 937, 970
with Brownian bridge, 125
SDE discretization, 108
second-order scheme, 119, 121
seed, 97
standard error, 97, 122
for digital option, 133
for greeks, 132, 135
strong convergence order, 111
strong law of large numbers, 96
strongly consistent, 109
third-order scheme, 468
upper bound for American option, 34-36, 163, 164
variance reduction, see variance reduction
weak convergence, 109
weak convergence order, 110
weakly consistent, 109
most likely path, see volatility, implied, most likely path approximation
multi-rate vanilla derivative, 763-813
copula method, see copula method
Libor market model, 807
observation lag, 782
stochastic volatility, see multistochastic volatility model
term structure models, 806
multi-stochastic volatility model, 800-806, 1149
correlation impact, 803
measure change by CMS caplet calibration, 802
measure change by drift adjustment, 801
Monte Carlo
Quadratic-Exponential scheme, 803
multi-rate vanilla derivative, 800-806
multi-tranche, see CLE, multi-tranche
non-central chi-square distribution, 284
asymptotics, 392
CDF, 102, 319
in CEV model, 283
in delta-gamma VaR/cVaR, 998
in LS model, 517
two-dimensional, 517
Normal model, XXXVIII, 283
CMS spread, 774
vega to swaptions, 775
numeraire, 10, 171
change of numeraire, 12
Girsanov's theorem, see Girsanov's theorem
discrete money market account, XXXVIII, 175
money market account, XXXVIII, 22, 28, 172

OIS, see overnight index swap one-dimensional integral for spread option, 787
operator calculus, 998-999
OTC market, see over-the-counter market
out-of-model adjustment, 951-971
adjusters method, 954-956 algorithm, 955
as control variate, 955
volatility adjustment, 956
asset-based adjustment, 963-964 CMS spread option, 964
coupon calibration, 952-954
delta-adjustment method, 956
extended calibration, 953
fee adjustment method, 967-969 additive, 968
blended, 968
impact on derivatives, 968
multiplicative, 968
issues, 961,964
mapping function adjustment, 965
market adjustment, 965
path re-weighting method, 956-961
as control variate, 961
Boltzman-Gibbs distribution, 959
Boltzman-Gibbs weights, 959
dual, 961
inappropriate use, 958 partition function, 958 risk sensitivities, 961
PDE for coupon values, 953
proxy model method, 961
spread adjustment method, 966
strike adjustment method, 969-971
impact on derivatives, 970
over-the-counter market, 193
overhedge, 1023
overlay curve, see yield curve, overlay curve
overnight index swap, 193, 200, 266

P\&L, 696, 991-995
P\&L analysis, 986
P\&L attribution, see $\mathrm{P} \& \mathrm{~L}$ explain
P\&L explain, 993-995
bump-and-do-not-reset explain, see P\&L explain, waterfall explain
bump-and-reset explain, 994-995
waterfall explain, 993-994
P\&L explanation, see P\&L explain
P\&L of hedged book, 987-990
P\&L predict, see P\&L prediction analysis
P\&L prediction analysis, 258, 991-993
first-order, 991
second-order, 991
unpredicted P\&L, 991
par rate, see forward swap rate
parameter averaging, see calibration, time averaging
partial differential equation, see PDE
partition function, 958
pathwise delta approximation, see pathwise differentiation method, pathwise delta approximation
pathwise differentiation method, 135-139, 1035-1060
adjoint method, 1056
computational complexity, 1053, 1057
barrier option, see barrier option, pathwise differentiation method
Bermudan swaption, see Bermudan swaption greeks, pathwise differentiation method

CLE, see CLE greeks, pathwise differentiation method computational complexity, 1052, 1053
discontinuous payoff, 1042, 1061
European option, 1054
gamma, 1050, 1056
generalized trigger product, see generalized trigger product, pathwise differentiation method
Libor market model, see Libor market model, pathwise differentiation method
money market account, 1046
Monte Carlo models, 1051-1060
pathwise delta approximation, 1059
PDE models, 1044-1050
sensitivity path generation, 138-139
TARN, see TARN, pathwise
differentiation method
vega, 1050, 1056
payoff smoothing, 1001-1034
adaptive integration, 1006
adding singularity to grid, 78,1007
barrier option, 1074-1077
benefits, 1012
Bermudan swaption, see CLE greeks, tube Monte Carlo
box smoothing, 1015-1018
multiple dimensions, 1020
on discrete grid, 1015
by importance sampling, 1065-1077
CLE, see CLE greeks, tube Monte Carlo
continuity correction, 59, 1012
fuzzy logic, 1028
gamma, 1019
grid shifting, 1007
hat smoothing, 1019
integration, 1012
Lagrange basis, 59, 1019
locality, 1019
Monte Carlo, 1022-1030
moving average, 1012, 1013
choice of window, 1014
multiple dimensions, 1019-1022
box smoothing, 1020
dominant dimension, 1022
one dimension, 1014

## Index xliii

partial analytical integration, 76-78, 1010
partial coupons, 1028
PDE, 1012
piecewise smooth function on a grid, 1016
singularity removal, 1009
TARN, see TARN, payoff smoothing; TARN, tube Monte Carlo
tube Monte Carlo, see tube Monte Carlo
PCA, see Principal Components Analysis
PDE, 18, 43-93
A-stable scheme, 55
ADI scheme, 43, 82-85
boundary conditions, 85
Asian option, 70
backward induction, 51
Black-Scholes, see Black model, PDE
boundary conditions for barrier options, 64 from PDE itself, 385,424
linear at boundary, 48
log-linear at boundary, 48
Cauchy problem, 18, 44
centering, 561
conditional stability, 55
consistent scheme, 56
convection-dominated, 61-64
convergent scheme, 56
coupon-paying, 67
Craig-Sneyd scheme, see PDE, predictor-corrector scheme
Crank-Nicolson scheme, 50
American options, 69
not strongly A-stable, 55
oscillations, 55,58
Dirichlet problem, 44, 64 space discretization, 46
dividends, 67, 68
domain truncation, 44 stability of greeks, 1002
Douglas-Rachford scheme, 85, 91 boundary conditions, 85
early exercise, 69
exponentially fitted schemes, 63
extra state variable method, see PDE, path-dependent options for implied volatility, see volatility, implied, PDE for
forward equation, see Kolmogorov forward equation
fully implicit scheme, 50
greeks off grid, 1005
L-stable scheme, 55
Lagrange basis, 58, 59
Lax equivalence theorem, 56
local volatility model, see local volatility model, PDE
mesh refinement, 73, 79
equidistant blocks, 74
non-equidistant, 75
multi-dimensional, 92
multi-exercise, 71
multi-level time-stepping, 58
non-equidistant discretization, 56
Nyquist frequency, 59
odd-even effect, 59
operator splitting, 82
orthogonalization, 86
drawbacks, 88
partial analytical integration, see payoff smoothing, partial analytical integration
path-dependent options, 69, 71, 868, 870, 896, 899, 932, 934
Peaceman-Rachford scheme, 84
boundary conditions, 85
predictor-corrector scheme, 89-92
quantization error, 59
Rannacher stepping, 58-61, 67, 457
semi-Lagrangian methods, 64
Shannon Sampling Theorem, 59
similarity reduction, 71
sinh transform, 384
smoothing, 58-61
continuity correction, 59
grid dimensioning, 1002
grid shifting, 60, 1002
space discretization, 45
stable scheme, 53
strongly A-stable scheme, 55
time discretization, 49
theta scheme, 50
two-dimensional, 80
two-dimensional with mixed derivatives, 86,89
upwinding, 62
variable transform, 44
von Neumann method, 53-56
amplification factor, 54
stability criterion, 54
well-posed, 56
Poisson distribution, 102
portfolio replication, see Bermudan swaption greeks, portfolio replication for hedging
power Gaussian copula, see copula, power Gaussian
predictor-corrector, $89,115,382,641$
Monte Carlo, see Monte Carlo, predictor-corrector
PDE, see PDE, predictor-corrector scheme
present value of a basis point, see swap, annuity
principal component, 105
Principal Components Analysis, 105, 106, 498, 602-604
principal factor, 105
product integral, 484
Profit-And-Loss, see P\&L
pseudo-Gaussian model, see quasiGaussian model
pseudo-random number generator, see Monte Carlo, random number generation, pseudo-random
put-call parity, 24
PVBP, see swap, annuity
QG model, see quadratic Gaussian model
qG model, see quasi-Gaussian model
quadratic covariation, XXXVII, 7
quadratic Gaussian model, 441, 518-533
as affine model, 519
benchmark rate parameterization, 525
Bermudan swaption, see Bermudan swaption calibration, local projection method, quadratic Gaussian model
bond dynamics, 521
bond reconstitution formula, 520
calibration, 531-532
multi-pass bootstrap, 531
CLE, see CLE calibration, local projection method, quadratic Gaussian model
CMS spread option, see CMS spread option, quadratic Gaussian model
curve factor, 523
European swaption, 526-531
approximations, 528
exact, 527
Fourier integration, 529
rank-2 approximation, 530
Fourier integration, 530
mean-reverting state variables, 519
moment-generating function, 529
Monte Carlo, 533
one-factor, 441
parameterization, 523-526
PDE, 533
quadratic approximation to swap rate, 529
short rate, 519
short rate in SV form, 525
short rate state distribution
in annuity measure, 526
in forward measure, 521
short rate state dynamics, 441, 519
in forward measure, 521
in annuity measure, 526
smile generation, 523-524
spanned stochastic volatility, 523, 532
TARN, see TARN, local projection method, quadratic Gaussian model
volatility factor, 523
volatility smile, 531
volatility swap, see volatility swap, quadratic Gaussian model
quadratic variation, XXXVII, 7
quadratic volatility model, 287-291
European call option value, 290
European put option value, 290, 291
Markovian projection, 1137
measure change, 289
small-noise expansion, 308

## Index xly

smile dynamics, 350
strict supermartingale, 288
time-dependent, 308
Quadratic-Exponential scheme, see square-root process, Monte Carlo, Quadratic-Exponential scheme
multi-dimensional, see multistochastic volatility model, Monte Carlo, QuadraticExponential scheme
quadrature, 531, 786
Gauss-Hermite, 531, 787
Gauss-Legendre, 786
Gauss-Lobatto, 786
quanto CMS, 744-748
annuity mapping function, 748
convexity adjustment, 747-748
copula method, 747
quanto adjustment, 745
replication method, 746
quasi-Gaussian model, 537-587
Bermudan swaption, see Bermudan swaption calibration, local projection method, quasi-Gaussian model
bond reconstitution formula, 538
calibration, 581
CEV local volatility, 545
CLE, see CLE calibration, local projection method, quasi-Gaussian model
CMS convexity adjustment, see CMS, convexity adjustment, quasi-Gaussian model
density approximation, 583
direct integration, 558, 583
Libor-with-delay, see Libor-withdelay, quasi-Gaussian model
linear local volatility, 545-548
calibration, 548
European swaption, 547
for swaption strip, 547
swap rate dynamics, 546
swap rate inter-temporal correlation, 555
swap rate variance ratio, 553
Markovian projection, 541, 564, 577, 1139
mean reversion, see mean reversion
mean reversion calibration, see mean reversion calibration
Monte Carlo, 563
Euler scheme, 563
multi-factor, 572-583
benchmark rate correlations, 582
benchmark rate parameterization, 574
bond reconstitution formula, 574
calibration to spread options, 582
correlation smile, 582
loadings, 582
local volatility, 574
Monte Carlo, 583
PDE, 582
short rate state distribution in annuity measure, 577
short rate state dynamics, 573
stochastic volatility, 574-583
swap rate dynamics, 576-581
swap rate dynamics by Markovian projection, 577
one-factor local volatility, 539
short rate state dynamics, 539
PDE, 560-563
convection-dominated, 561
domain truncation, 562
space discretization, 561
short rate state distribution, 559
short rate state dynamics, 538
in annuity measure, 542, 543
in forward measure, 583
single-state approximation, 563-567
small-time asymptotics, 559
stochastic volatility, 567-572
bond reconstitution formula, 568
calibration, 570-571
Monte Carlo, 572
non-zero correlation, 572
PDE, 572
swap rate dynamics, 568-570
unspanned, 568
swap rate dynamics, 540-545, 549
approximate, 541-545
approximate linear, 542
approximate quadratic, 545
swap rate variance, 544
swap rate volatility, 540

TARN, see TARN, local projection method, quasi-Gaussian model volatility swap, see volatility swap, quasi-Gaussian model

Radon-Nikodym derivative, 9, 1067
range accrual, 211
CMS, 211
CMS spread, 211, 764
curve cap, 212, 764
dual, 212, 764
floating, 764
product-of-ranges, 212
ratchet swap, 212
relative entropy, 957
replication method, 337, 722
CMS, see CMS, convexity adjustment, replication method
European option, see European-style option, replication method
Libor-in-arrears, see Libor-inarrears, replication method
Libor-with-delay, see Libor-withdelay, replication method
semi-static, 939
reserve, 986
rho, 980
Riccati, 364
Riemann zeta function, 128
risk limit, 986
risk measure, 996
coherent, 996
risk sensitivities, 1093
common definitions, 980
delta, see delta
grid dimensioning for stability, 1002
grid shifting for stability, 1002
Jacobian method, 254-258, 985, 986, 1105, 1106, 1111, 1118, 1119, 1121
off PDE grid, 1005
perturbation approach, 1050
vega, see vega
root search, 99
Newton-Raphson method, 99, 116, 235
secant method, 235
Runge-Kutta method, 116, 365, 432, 434, 514
running maximum, 124
running minimum, 124

SABR model, 343-345, 357, 951, 1121 ad-hoc improvements, 703
density tail, 760
moment explosion, 344
volatility smile expansion, 345
SALI tree, see tree, SALI
sausage Monte Carlo, see tube Monte Carlo
SDE, see diffusion, SDE
SDE discretization, see Monte Carlo, SDE discretization
Sharpe ratio, 22
shifted log-normal model, see displaced log-normal model
short rate, 169
short rate model, 172
affine, see affine short rate model
affine one-factor, see affine short rate model, one-factor
Black-Derman-Toy, see Black-Derman-Toy model
calibration to yield curve, 455
forward induction, 456
forward-from-backward induction, 458
Cox-Ingersol-Ross, see Cox-IngersolRoss model
Dybvig parameterization, 461-463, 466
HJM representation, 462
econometric, 449
empirical estimation, 449
forward volatility impact on Bermudan swaption, 876
Gaussian approximation, 1064
Gaussian model for basis spread, 681
Gaussian short rate, see Gaussian short rate model
Hagan and Woodward parameterization, 463-466
Ho-Lee, see Ho-Lee model
importance sampling, 1063-1065
log-normal, 443-449
issues, 445

## Index xlvii

Sandmann-Sondermann transform, 446
Monte Carlo, 467-469
Euler scheme, 467
Milstein scheme, 467
payoff construction issues, 468
SDE discretization, 467
variance reduction, 468
multi-factor, 477
path independence, 444
PDE, 454-455
domain truncation, 454
power-type, 449
quadratic Gaussian, see quadratic Gaussian model
quasi-Gaussian, see quasi-Gaussian model
time-stationary, 416
volatility calibration, 459-461
multi-pass bootstrap, 461
shout option, 935
on capped coupon, 935
optimal stopping time, 936
similarity reduction, 71, 869
CLE, see CLE valuation, PDE, similarity reduction
PDE, see PDE, similarity reduction
single-rate vanilla derivative, 695-762
approximately single-rate, 707
cap, see cap
CMS cap, see CMS cap
CMS floor, see CMS floor
CMS swap, see CMS swap
ED future, see ED future
European swaption, see European swaption
futures contract, see ED future
Libor-in-arrears, see Libor-in-arrears
Libor-with-delay, see Libor-withdelay
range accrual, see range accrual singular value, 860
singular value decomposition, see CLE regression, SVD decomposition
truncated, see CLE regression, truncated SVD decomposition singularity removal, see payoff smoothing, singularity removal
skew vega, see vega, skew vega
smile vega, see vega, smile vega
snowball, see CLE, snowball
snowbear, 213
snowrange, 213
snowstorm, 213
Sonia, 193, 200
spline, 230, 270-275
Catmull-Rom, 238, 240, 271, 272
cubic $C^{2}, 273-274$
cubic smoothing, 248
exponential tension spline, 243
Hermite cubic, 238, 270-273
interpolating, 248
Kochanek-Bartels, 272
least-squares regression, 248
natural, 241
natural cubic, 273
shape preserving, 275
smoothing, 234
TCB, see spline, Kochanek-Bartels
tension, 240, 243, 244, 246, 247, 250, 272, 274-275
convergence to piecewise linear, 275
tension factor, 243
spot Libor measure, see measure, spot
spot rate, see short rate
square-root process, 315
$\mathrm{E}(\sqrt{z}), 1153,1155$
basic properties, 318-320
boundary behavior, 319
conditional CDF, 319
conditional moments, 319
Feller condition, 319
moment-generating function, 322 , 342, 364, 372
time-dependent parameters, 364
moments, 375
Monte Carlo, 388-394
Euler scheme, 389
exact simulation, 388
full truncation scheme, 389
higher-order schemes, 389
log-normal approximation, 390
moment-matching schemes, 390
Quadratic-Exponential scheme, 392, 394
truncated Gaussian scheme, 391
multi-dimensional, 1152
xlviii Index

PDF, 1153, 1156
stationary distribution, 320,383
static replication, 210, 717
CMS, see CMS, convexity adjustment, replication method
European option, see European-style option, replication method
Libor-in-arrears, see Libor-inarrears, replication method
Libor-with-delay, see Libor-withdelay, replication method
stochastic optimization method, 953
stochastic volatility model, 315-402, 569, 570, 1140
as interpolation rule, 701
ATM volatility, 348
basket option, see Markovian projection, basket option in SV model
calibration, 701-702
calibration norm, 702
normalization, 702
caplet calibration, 705
CEV type, see SABR model
CMS convexity adjustment, 738
correlation, 347
dampening constant, 325
delta, 697
effective skew, 373
effective volatility, 371, 372
effective volatility of variance, 375
European option, 327
control variate, 328
volatility mixing, 339
explicit solution, 320
for CMS rate, 738-742
dynamics in forward measure, 739
Fourier integration, 324-339
arbitrary European payoffs, 336, 338
convolution, 325
direct integration, 330
discrete, 330
FFT, 330
for variance, 339-343
integration bounds, 330
strip of convergence, 329
with control variate, 328,330
hedging, 353-358
level parameter, 317
link between forward and annuity measures, 739
LSV, see local stochastic volatility model
martingale property, 320
mean reversion speed, $316,317,348$
half-life, 318
measure change, 322
moment explosion, 323
moment-generating function, 321, 324, 327
branch cut, 330
singularities, 329
time-dependent parameters, 364
Monte Carlo, 387-397
Broadie-Kaya scheme, 394
Broadie-Kaya simplified scheme, 396
exact scheme, 394
martingale correction, 397
Taylor-type schemes, 396
variance process, see square-root process, Monte Carlo
multi-dimensional, see multistochastic volatility model
PDE, 381-387
boundary conditions for stochastic variance, 385
boundary conditions from PDE itself, 385
discretizing spot, 387
discretizing stochastic variance, 383
for forward Kolmogorov equation, 386
predictor-corrector, 382
quadratic discretization, 384
range for spot, 386
range for stochastic variance, 382
sinh transform, see PDE, sinh transform
sinh-quadratic discretization, 384
variable transform, 383, 384
process for variance, see square-root process
skew, 317, 346
smile dynamics, 347-349, 351, 353, 354

## Index xlix

SV volatility, 317
time-dependent, 363-402
asymptotic expansion, 366-370
averaging, see calibration, time averaging
Fourier integration, 363, 366
volatility of variance, $316,317,346$
volatility of volatility, 318
stopping time, 6
straddle, 223
strategy, 7
doubling, 10
gains process, 8
permissible, 9
replicating, 11
self-financing, 8,17
Stratonovich integral, 5
strike price, 24
structured note, see exotic swap
structured swap, see exotic swap
Student's $t$-distribution, 101
Monte Carlo, 101
survival measure
Bermudan swaption, see Bermudan swaption, survival measure
importance sampling, see importance sampling, survival measure
SV model, see stochastic volatility model
SV model with general variance process, 359-361
martingale properties, 360
moment explosion, 361
properties, 359
stationary distribution, 360
strict supermartingale, 360
SVD, see CLE regression, SVD decomposition
SVI model, see volatility smile, SVI
swap, 197
accreting, 200
amortizing, 200
annuity, XXXVIII, 199
annuity factor, 170
averaging, see averaging cash flow
cash-settled, 744
CMS, see CMS swap
effective date, 225
fixed-floating, 198, 199, 230, 231
valuation formula, 199
fixing dates, 198
legs, 197
Libor-in-arrears, see Libor-in-arrears
Libor-with-delay, see Libor-withdelay
par rate, see forward swap rate
payer, 203
payment dates, 198
receiver, 203
swap rate, see forward swap rate
swap market model, 617, 675-677
swap measure, see measure, annuity
swap rate, see forward swap rate
swaption grid, see European swaption, swaption grid

Tanaka extension of Ito's lemma, 7, 26, 294, 1131
targeted redemption note, see TARN
TARN, 217, 218, 925-933
cap at trigger, 219
global model, 927
impact of inter-temporal correlation, see inter-temporal correlation, impact on TARNs
importance sampling, 1068-1077
one-step survival conditioning, 1069
removing first digital, 1068
leverage, 927
Libor market model, 927
lifetime cap, see TARN, cap at trigger
lifetime floor, see TARN, make whole
local projection method, 928-931
Gaussian short rate model, 929
Markov-functional model, 931
quadratic Gaussian model, 931
quasi-Gaussian model, 931
make whole, 219
Markov-functional model, 473
multi-factor quasi-Gaussian model, 927
partial analytical integration, 1011
pathwise differentiation method, 1044

## Index

payoff smoothing, 1011, 1029, 1068-1077
PDE, 931-933
cap at trigger, 933
make whole, 933
Monte Carlo pre-simulation, 933
upper bound for extra state variable, 932
tube Monte Carlo, 1029
valuation formula, 218
volatility smile, 927, 929-931
tenor structure, XXXVIII, 170
index function, 591
tension spline, see spline, tension
term parameters, 378
term structure model, 202, 277
terminal swap rate model, 707-714
annuity mapping function, 708,713 , $722,724-725,728,730,732$
as conditional expected value, 724-725
calibration to market, 728
forward swap rate condition, 733
forward value condition, 732
in measure change, 735
linear approximation, 728
LM model, see Libor market model, annuity mapping function
mean reversion, see CMS, convexity adjustment, impact of mean reversion
multi-rate, 765
swap rate squared condition, 733
CMS convexity adjustment, see CMS, convexity adjustment, linear TSR model
consistency condition, 708
exponential TSR model, 712-713
Libor-with-delay, see Libor-withdelay, swap-yield TSR model
linear TSR model, 709
CMS convexity adjustment, see CMS, convexity adjustment, linear TSR model
forward CMS straddle, 941
mean reversion parameterization, 710
swap rate distribution in forward measure, 736, 737
vega hedging, 712
loading from Gaussian model, 712
no-arbitrage condition, 708
PDF of swap rate in forward measure, 737
from CMS caplets, 737
reasonableness, 708
swap rate distribution in forward measure, 736
swap-yield TSR model, 713-714
CMS convexity adjustment, see CMS, convexity adjustment, swap-yield TSR model
theta, 980,992
rolling yield curve, 992
Tikhonov regularization, see CLE regression, Tikhonov regularization
time decay, 52
time value, 27
"tip-top", see "flip-flop"
tower rule, see iterated conditional expectations
tree, 423
binomial, 444, 456
SALI, 78
trinomial, 51, 456
truncated Gaussian scheme, see square-root process, Monte Carlo, truncated Gaussian scheme
TSR model, see terminal swap rate model
tube Monte Carlo, 1022-1030
barrier option, see barrier option, tube Monte Carlo
Bermudan swaption, see CLE greeks, tube Monte Carlo
CLE, see CLE greeks, tube Monte Carlo
digital option, 1024
discrete knock-in barrier, 1028
generalized trigger product, see barrier option, tube Monte Carlo
partial coupons, 1028
TARN, see TARN, tube Monte Carlo
underhedge, 1023
uniform distribution, XXXVII, 768
universal law of volatility, 1137
upwinding, see PDE, upwinding
value-at-risk, 499, 975, 996-998
conditional, 996
delta VaR, 998
delta-gamma VaR/cVaR, 998
Gaussian, 997
historical, 996
vanilla derivative, 695-813
multi-rate, see multi-rate vanilla derivative
single-rate, see single-rate vanilla derivative
vanilla model, 202, 277, 315, 1121, 1129
for multi-rate derivative, see multi-rate vanilla derivative
for single-rate derivative, see single-rate vanilla derivative
local volatility model, see local volatility model
stochastic volatility model, see stochastic volatility model
vanna, 980
VaR, see value-at-risk
variance reduction, 143-158
antithetic variates, 144
efficiency, 145
non-Gaussian, 145
common random number scheme, 132, 134
conditional Monte Carlo, 127
control variate, see control variate from hedging strategy, see control variate, dynamic
importance sampling, see importance sampling
moment matching, 146
systematic sampling, 145
Vasicek model, 411-413
bond reconstitution formula, 412
bond volatility, 413
forward rate volatility, 413
short rate distribution, 411
short rate dynamics, 411
yield curve shapes, 412
vega, $355,980,1095-1125$
additivity, 1103
Bermudan swaption, 1114
bucketed shocks, 1099
CMS spread option, 1116, 1120
constant Libor correlations, 1120
constant Libor correlations, 1115, 1120
constant term swap correlations, 1116, 1118-1120
cumulative shocks, 1099
direct method, 1098-1102, 1110
Bermudan swaption, 1103
European swaption, 1102
second-order effects, 1111
European swaption, 1113, 1114
flat shock, 1099
forward swaption straddle, 948
"good", 1102-1105
hybrid method, 1111-1113
algorithm, 1112
Bermudan swaption, 1114
CMS spread option, 1116
European swaption, 1113, 1114
in LM model
coverage, 884
indirect method, 1105-1111, 1121
Bermudan swaption, 1109
European swaption, 1108
least-squares problem, 1106
locality, 1107
smoothing, 1107
Jacobian method, see vega, indirect method; risk sensitivities, Jacobian method
Libor market model, 1095-1125
bootstrap calibration, 1111, 1112
multi-factor, 1115
projection, 1123
local projection method, 867
local vs. global, 1097
locality, 1104
benchmark set locality, 1104
exotic locality, 1104
full set locality, 1104
market vega, 984, 1096, 1110
model vega, 984, 1096, 1124-1125
pathwise differentiation method, see pathwise differentiation method, vega
projection, 1122-1124
relationship to gamma, 981
row shocks, 1099
running cumulative shocks, 1099
scaling, 1103
skew vega, 1113-1115
smile vega, 1113-1115
volatility, 27
average convexity, 307
Bachelier, see volatility, Normal
basis point, see volatility, Normal
Black, XXXVIII, 204
bp, see volatility, Normal
CEV, 280, 623
Dupire's, see Dupire local volatility factor volatility, 499
forward volatility of Libor rate, 817
Gaussian, see volatility, Normal implied, 278
as average of realized, 989
effects of mis-specification, 987
most likely path approximation, 990
PDE for, 296
local, see Dupire local volatility
Normal, 204, 283, 623
Normal for CMS spread option, 774
separable, 300
small-noise expansion, 307
spanned stochastic volatility, 452
spot volatility, 817
spread, 774
strike-dependent, 775
stochastic, see stochastic volatility model
unspanned stochastic volatility, 443
"volatility squeeze", 422
volatility cube, see European swaption, volatility cube
volatility derivative, see forward volatility derivative
volatility skew, 279
volatility smile, 279, 315
ATM backbone, 699, 700
backbone, 696
adjustable, 697-700
curvature, 1138
dynamics, 279, 348, 696-700, 818
sticky delta, 350, 697
sticky strike, 352, 697
forward skew, 944

Gaussian backbone, 698
impact on forward volatilities, see forward volatility, impact of volatility smile
impact on inter-temporal correlations, see inter-temporal correlation, impact of volatility smile
probability density from, 278
SABR, see SABR model
shadow delta hedging, 697
skew vega, 1114
skew-dominated, 352
slope, 279
smile vega, 1114
SVI, 703, 951, 1121
upward sloping, 281
vega, 1114
volatility structure, 815
volatility swap, 220, 221, 933-945
capped, 937
CMS spread, 221
copula method, see copula method, volatility swap
fixed-expiry, 221, 940
fixed-tenor, 221, 940
impact of forward volatility, 944
impact of volatility smile dynamics, 941
Libor market model, 933, 934
local projection method, 934
min-max, see min-max volatility swap
PDE, 934
quadratic Gaussian model, 941
quasi-Gaussian model, 941
with barrier, 222
with shout, 221, 935
volga, 980
Volterra integral equation, 436
vomma, 980
Wiener process, see Brownian motion
year fraction, 224
yield curve, 191, 230, 231, 233
base index curve, 268
basis risk, 270
benchmark set, 230
forecasting curve, see yield curve, index curve
index curve, 261, 267, 677
index-discounting basis, 197, 261
instantaneous forward curve, 233
joint evolution of discount and
forward curves, 677
multi-index curve group, 267-270
overlay curve, 259
perturbation locality, 230, 251-253, 258
Principal Components Analysis, see Principal Components Analysis
ringing, 235, 242, 243, 252
smooth, 258
spread curve, 269, 884
tenor basis, 230,267
TOY effect, 258
yield curve construction, 229-275
benchmark set, 231
bootstrapping, 234
flat forward, 236
linear yield, 235
constrained optimization, 248
cross-currency, 259
cross-currency arbitrage, 260
cubic spline $C^{2}, 240-243$
problems, 242
curve overlays, 258
FX forwards, 259
Hermite spline, 238-240
iterative solution, 239
Jacobian rebuild, 256
multi-index curve group, 230, 265
non-parametric fitting, 245-250
norm specification, 245
optimization algorithm, 245
separate discount and forward curves, 260
spline, see spline
spline fitting, 234-244
tension spline, 243-244
yield curve risk, 250-258
cumulative shifts, 256, 257
forward rate approach, 252
Jacobian method, see risk sensitivities, Jacobian method
par-point approach, 251
rolling for theta, 992
waterfall approach, see yield curve risk, cumulative shifts
yield curve spread option, see CMS spread option
zero-coupon bond, see discount bond zero-coupon bond option, 185

