

	Contents	page
<b>Contents</b>		xviii
<b>1 Introduction</b>		1
1.1 Overview		1
1.2 Outline of the Book		4
<b>2 Vector Autoregressive Models</b>		19
2.1 Stationary and Trending Processes		19
2.2 Linear VAR Processes		23
2.2.1 The Basic Model		23
2.2.2 The Moving Average Representation		26
2.2.3 VAR Models as an Approximation to VARMA Processes		27
2.2.4 Marginal Processes, Measurement Errors, Aggregation, Variable Transformations		28
2.3 Estimation of VAR Models		30
2.3.1 Least-Squares Estimation		31
2.3.2 Restricted Generalized Least Squares		34
2.3.3 Bias-Corrected LS		35
2.3.4 Maximum Likelihood Estimation		38
2.3.5 VAR Processes in Levels with Integrated Variables		41
2.3.6 Sieve Autoregressions		43
2.4 Prediction		46
2.4.1 Predicting from Known VAR Processes		46
2.4.2 Predicting from Estimated VAR Processes		47
2.5 Granger Causality Analysis		48
2.6 Lag-Order Selection Procedures		51
2.6.1 Top-Down Sequential Testing		51
2.6.2 Bottom-Up Sequential Testing		52
2.6.3 Information Criteria		54

2.6.4	Recursive Mean-Squared Prediction Error Rankings	57
2.6.5	The Relative Merits of Alternative Lag-Order Selection Tools	58
2.7	Model Diagnostics	66
2.7.1	Tests for Autocorrelation in the Innovations	67
2.7.2	Tests for Nonnormality	67
2.7.3	Residual ARCH Tests	68
2.7.4	Time Invariance	69
2.8	Subset VAR Models, AVAR Models, and VARX Models	72
2.8.1	Subset VAR Models	72
2.8.2	Asymmetric VAR Models	73
2.8.3	VARX Models	74
<b>3</b>	<b>Vector Error Correction Models</b>	75
3.1	Cointegrated Variables and Vector Error Correction Models	75
3.1.1	Common Trends and Cointegration	75
3.1.2	Deterministic Terms in Cointegrated Processes	80
3.2	Estimation of VARs with Integrated Variables	82
3.2.1	The VAR(1) Case	82
3.2.2	Estimation of VECMs	86
3.2.3	Estimation of Levels VAR Models with Integrated Variables	95
3.3	Model Specification	99
3.3.1	Choosing the Lag Order	99
3.3.2	Specifying the Cointegrating Rank	100
3.4	Diagnostic Tests	104
3.5	The Benefits of the VECM Representation	105
3.6	Practical Issues	105
3.6.1	Limitations of Tests for Unit Roots and Cointegration	106
3.6.2	Alternative Approaches	106
<b>4</b>	<b>Structural VAR Tools</b>	109
4.1	Structural Impulse Responses	110
4.2	Forecast Error Variance Decompositions	113
4.3	Historical Decompositions	116
4.4	Forecast Scenarios	123
4.4.1	Conditional Forecasts Expressed in Terms of Sequences of Structural Shocks	124
4.4.2	Conditional Forecasts Expressed in Terms of Sequences of Observables	130
4.5	Simulating Counterfactual Outcomes	131
4.6	Policy Counterfactuals	136

<b>5 Bayesian VAR Analysis</b>	140
<b>5.1 Basic Terms and Notation</b>	141
5.1.1 Prior, Likelihood, Posterior	141
5.1.2 Bayesian Estimation and Inference	142
5.1.3 Simulating the Posterior Distribution	145
<b>5.2 Priors for Reduced-Form VAR Parameters</b>	149
5.2.1 General Procedures for Choosing the Parameters of Prior Densities	150
5.2.2 Normal Prior for the VAR Parameters for Given $\Sigma_u$	151
5.2.3 The Original Minnesota Prior	155
5.2.4 The Natural Conjugate Gaussian-Inverse Wishart Prior	162
5.2.5 The Independent Gaussian-Inverse Wishart Prior	166
<b>5.3 Extensions and Related Issues</b>	169
<b>6 The Relationship between VAR Models and Other Macroeconometric Models</b>	171
<b>6.1 The Relationship between VAR Models and Traditional Dynamic Simultaneous Equations Models</b>	171
6.1.1 The VAR Representation of Traditional DSEMs	172
6.1.2 Incredible Restrictions in Traditional DSEMs	174
6.1.3 Structural VAR Models as an Alternative to Traditional DSEMs	176
<b>6.2 The Relationship between VAR Models and DSGE Models</b>	177
6.2.1 Basics	177
6.2.2 The Role of Data Transformations	180
6.2.3 Why Not Use VARMA Models?	180
6.2.4 Autoregressive Sieve Approximations of VAR( $\infty$ ) Processes	181
6.2.5 Summary of Potential Problems in Approximating DSGE Models with VAR Models	182
<b>6.3 DSGE Models as an Alternative to VAR Models?</b>	183
6.3.1 Calibrated DSGE Models	184
6.3.2 Estimated DSGE Models	185
6.3.3 Calibration versus Bayesian Estimation	186
6.3.4 Are Structural VAR Models Less Credible than DSGE Models?	187
6.3.5 Are DSGE Models More Accurate than VAR Models?	189
6.3.6 Policy Analysis in DSGE Models and SVAR Models	191
<b>6.4 An Overview of Alternative Structural Macroeconometric Models</b>	193

6.4.1	Combining DSEM <sup>s</sup> and SVAR Models	193
6.4.2	Combining DSGE and SVAR Models	194
<b>7</b>	<b>A Historical Perspective on Causal Inference in Macroeconomics</b>	<b>196</b>
7.1	A Motivating Example	196
7.2	Granger Causality Tests for Covariance Stationary VAR Models	197
7.3	Granger Causality, Predeterminedness, and Exogeneity	199
7.3.1	Basic Concepts	199
7.3.2	Granger Causality and Forward-Looking Behavior	201
7.3.3	Strict Exogeneity in Modern Macroeconomic Models	203
7.4	The Demise of Granger Causality Tests in Macroeconomics	204
7.5	Responses to Unanticipated Changes in Money Growth	205
7.5.1	The Narrative Approach	205
7.5.2	Exogenous Shocks Derived from Data-Based Counterfactuals	208
7.5.3	News Shocks	209
7.5.4	Shocks to Financial Market Expectations	210
7.5.5	Summary	211
7.6	Structural VAR Shocks	211
7.6.1	The Identification Problem	212
7.6.2	The Relationship between Structural VAR Shocks and Direct Shock Measures	213
7.6.3	Causality in Structural VAR Models	214
<b>8</b>	<b>Identification by Short-Run Restrictions</b>	<b>216</b>
8.1	Introduction	216
8.2	Recursively Identified Models	219
8.3	Sources of Identifying Restrictions	221
8.4	Examples of Recursively Identified Models	224
8.4.1	A Simple Macroeconomic Model	224
8.4.2	A Model of the Global Market for Crude Oil	225
8.4.3	Oil Price Shocks and Stock Returns	226
8.4.4	Models of the Transmission of Energy Price Shocks	227
8.4.5	Semistructural Models of Monetary Policy	228
8.4.6	The Permanent Income Model of Consumption	234
8.5	Examples of Nonrecursively Identified Models	235
8.5.1	Fiscal Policy Shocks	236
8.5.2	An Alternative Simple Macroeconomic Model	237
8.5.3	Discussion	237
8.5.4	The Graph-Theoretic Approach	238
8.6	Summary	239

<b>9 Estimation Subject to Short-Run Restrictions</b>	241
9.1 Model Setup	241
9.2 Method-of-Moments Estimation	242
9.2.1 Recursively Identified Models	242
9.2.2 Nonrecursively Identified Models	250
9.2.3 GMM Estimation of Overidentified Models	253
9.3 Instrumental Variable Estimation	258
9.4 Full Information Maximum Likelihood Estimation	262
9.5 Bayesian Estimation	265
9.6 Summary	268
<b>10 Identification by Long-Run Restrictions</b>	269
10.1 The Traditional Framework for Imposing Long-Run Restrictions	269
10.2 A General Framework for Imposing Long-Run Restrictions	272
10.2.1 The Long-Run Multiplier Matrix	272
10.2.2 Identification of Structural Shocks	275
10.3 Examples of Long-Run Restrictions	278
10.3.1 A Real Business Cycle Model with and without Nominal Variables	278
10.3.2 A Model of Neutral and Investment-Specific Technology Shocks	282
10.3.3 A Model of Real and Nominal Exchange Rate Shocks	284
10.3.4 A Model of Expectations about Future Productivity	284
10.4 Examples of Models Combining Long-Run and Short-Run Zero Restrictions	287
10.4.1 The IS-LM Model Revisited	287
10.4.2 A Model of the Neoclassical Synthesis	289
10.4.3 A U.S. Macroeconomic Model	290
10.5 Limitations of Long-Run Restrictions	292
10.5.1 Long-Run Restrictions Require Exact Unit Roots	292
10.5.2 Sensitivity to Omitted Variables	293
10.5.3 Lack of Robustness at Lower Data Frequencies	294
10.5.4 Nonuniqueness Problems without Additional Sign Restrictions	294
10.5.5 Sensitivity to Data Transformations	296
<b>11 Estimation Subject to Long-Run Restrictions</b>	297
11.1 Model Setup	297
11.2 Models Subject to Long-Run Restrictions Only	299
11.2.1 Method-of-Moments Estimation	301

11.2.2	Full Information Maximum Likelihood Estimation	306
11.2.3	Instrumental Variable Estimation	307
11.3	Models Subject to Long-Run and Short-Run Restrictions	310
11.3.1	Estimating the Model in VAR Representation	310
11.3.2	Estimating the Model in VECM Representation	316
11.4	Practical Limitations of Long-Run Restrictions	320
11.4.1	Estimators of the Long-Run Multiplier Matrix May Be Unreliable	321
11.4.2	Lack of Power	321
11.4.3	Near-Observational Equivalence of Shocks with Permanent Effects and Shocks with Persistent Effects	322
11.4.4	Weak Instrument Problems	322
11.5	Can Structural VAR Models Recover Responses in DSGE Models?	323
11.5.1	The Origin of This Controversy	323
11.5.2	The Position of Chari et al. (2008)	325
11.5.3	The Position of Christiano et al. (2006)	327
11.5.4	Understanding the Simulation Evidence	328
11.5.5	Summary	331
<b>12</b>	<b>Inference in Models Identified by Short-Run or Long-Run Restrictions</b>	<b>334</b>
12.1	Delta Method Intervals for Structural Impulse Responses	335
12.1.1	Finite-Order VAR Models	336
12.1.2	Infinite-Order VAR Models	338
12.1.3	Discussion	339
12.1.4	Extensions to Other Statistics	339
12.1.5	On the Choice of the Significance Level	340
12.2	Bootstrap Intervals for Structural Impulse Responses	340
12.2.1	The Standard Residual-Based Recursive-Design Bootstrap	341
12.2.2	The Standard Residual-Based Fixed-Design Bootstrap	345
12.2.3	The Residual-Based Wild Bootstrap	345
12.2.4	Bootstrapping Tuples of Regressands and Regressors	347
12.2.5	Block Bootstrap Methods	348
12.2.6	Alternative Bootstrap Confidence Intervals	356
12.3	Bootstrap Intervals Based on Bias-Adjusted Estimators	363
12.4	Potential Pitfalls in Impulse Response Inference	365
12.5	Finite-Sample Properties of Bootstrap Confidence Intervals	368

12.6	Inference for Integrated and Cointegrated VAR Processes	369
12.6.1	VAR Models in Differences	369
12.6.2	Vector Error Correction Models	370
12.6.3	Integrated and/or Cointegrated VAR Models in Levels	373
12.7	Inference in Local-to-Unity VAR Processes	377
12.7.1	Local-to-Unity Asymptotics	378
12.7.2	Inference in Levels for Local-to-Unity VAR Models	381
12.7.3	The Grid Bootstrap Method	382
12.7.4	A Hybrid Method	384
12.7.5	Implications for Second-Stage Inference after Pretesting	385
12.8	Local Projections	389
12.9	Synthesis	393
12.10	Bayesian Regions of Highest Posterior Density	394
12.10.1	Pointwise Inference on Structural Impulse Responses	395
12.11	Joint Inference on Structural Impulse Responses	398
12.11.1	Joint Confidence Sets for Structural Impulse Responses	399
12.11.2	Joint Credible Sets	406
12.12	Other Bootstrap Applications	410
12.12.1	Bootstrap Prediction	410
12.12.2	Bootstrapping the Critical Values of Test Statistics	411
12.13	Examples of Impulse Response Confidence Intervals	412
12.13.1	An Exactly Identified Model	412
12.13.2	Guarding against Conditional Heteroskedasticity	415
12.13.3	Extensions to Overidentified Models	416
<b>13</b>	<b>Identification by Sign Restrictions</b>	421
13.1	A Model of Demand and Supply	421
13.2	How to Impose Static Sign Restrictions	424
13.2.1	Givens Rotation Matrices	426
13.2.2	The Householder Transformation	427
13.2.3	The Ouliaris-Pagan Approach	428
13.3	Partially Identified VAR Models	430
13.4	Beyond Static Sign Restrictions	432

13.4.1	Dynamic Sign Restrictions	432
13.4.2	Elasticity Bounds	432
13.4.3	Shape Restrictions	435
13.5	Can Sign Restrictions Be Verified?	435
13.6	Estimation and Inference in Sign-Identified VAR Models	437
13.6.1	Frequentist Approaches	438
13.6.2	Bayesian Approaches	440
13.6.3	Evaluating the Posterior of the Structural Impulse Responses	442
13.6.4	The Penalty Function Approach	448
13.6.5	Using Historical Information to Narrow the Set of Admissible Models	451
13.7	The Role of the Prior for the Rotation Matrix	452
13.7.1	An Approach Based on Explicit Bayesian Priors for $B_0$	453
13.7.2	An Approach Based on Explicit Bayesian Priors for the Structural Impulse Responses	459
13.7.3	A Robust Bayesian Approach	461
13.7.4	An Agnostic Bayesian Approach	462
13.7.5	A Non-Bayesian Approach	463
13.8	Examples of Models Identified by Sign Restrictions	464
13.8.1	A Small-Scale Macroeconomic Model	464
13.8.2	A Slightly Larger Macroeconomic Model	465
13.8.3	A Model of Unemployment and Vacancies	466
13.8.4	An Extended Model of Unemployment and Vacancies	466
13.8.5	A Model of Technology Shocks	467
13.8.6	A Model of Exchange Rate Responses to Monetary Policy Shocks	467
13.8.7	A Medium-Scale Macroeconomic Model	468
13.8.8	A Model of Speculation in the Global Oil Market	469
13.9	Mixing Sign and Exclusion Restrictions	471
13.9.1	Examples of Models Mixing Sign and Short-Run Zero Restrictions	471
13.9.2	How to Combine Sign Restrictions and Exclusion Restrictions	474
13.9.3	Discussion	482
13.10	Empirical Illustrations	483
13.10.1	A Model of the Global Oil Market	483
13.10.2	A Model of Monetary Policy	485
13.11	Concluding Remarks	488

<b>14 Identification by Heteroskedasticity or Non-Gaussianity</b>	491
14.1 Introduction	491
14.2 The Model Setup	492
14.2.1 The Baseline Model	492
14.2.2 An Illustrative Example	494
14.2.3 The General Model	495
14.3 Alternative Volatility Models	496
14.3.1 Structural VAR Models with Extraneously Specified Volatility Changes	496
14.3.2 Structural VAR Models with Markov Switching in the Variances	505
14.3.3 Structural VAR Models with Smooth Transitions in the Variances	511
14.3.4 Structural VAR Models with GARCH Errors	517
14.4 Alternative Approaches Using Heteroskedasticity	524
14.4.1 Time-Varying Instantaneous Effects	525
14.4.2 Correlated Shocks	525
14.5 Identification by Non-Gaussianity	526
14.5.1 Independent Shocks	526
14.5.2 Uncorrelated Shocks	528
14.6 Discussion	530
<b>15 Identification Based on Extraneous Data</b>	532
15.1 Identification Based on High-Frequency Futures Prices	532
15.1.1 A Set-Identified Approach	534
15.1.2 A Point-Identified Approach	538
15.1.3 Discussion	542
15.2 Identification Based on External Instruments	542
15.2.1 Estimation and Inference	544
15.2.2 Discussion	548
<b>16 Structural VAR Analysis in a Data-Rich Environment</b>	549
16.1 Factor Models	551
16.1.1 Static Factor Models	551
16.1.2 Dynamic Factor Models	555
16.1.3 Selecting the Number of Factors	562
16.1.4 Structural Change	565
16.2 Factor-Augmented Structural VAR Models and Related Techniques	565
16.2.1 Structural FAVAR Models	565
16.2.2 Structural Analysis with DFM	571
16.2.3 Empirical Examples of FAVAR Models and DFM	577

16.3	Large Bayesian VAR Models	579
16.3.1	Priors for Large Bayesian VARs	580
16.3.2	Structural Identification in Large BVARs	583
16.4	Alternative Large-Dimensional VAR Models	584
16.4.1	Panel VARs	584
16.4.2	Global VARs	586
16.4.3	Spatial Models	587
16.5	Discussion	587
17	<b>Nonfundamental Shocks</b>	590
17.1	Introduction	590
17.2	Fundamental and Nonfundamental Moving Average Representations	592
17.3	Fundamental versus Nonfundamental Representations	594
17.3.1	Nonfundamental Shocks in Economic Models	594
17.3.2	Nonfundamentalness Due to MA Roots in the Unit Circle	596
17.3.3	Nonfundamentalness Due to Omitted Variables	597
17.3.4	Avoiding Nonfundamentalness by Using Factor-Augmented or Large Bayesian VARs	601
17.3.5	Other Approaches to Dealing with Anticipation	603
17.4	Conclusions	607
18	<b>Nonlinear Structural VAR Models</b>	609
18.1	Motivation	609
18.2	Nonlinear VAR Analysis	612
18.2.1	General Setup	612
18.2.2	Structural Analysis	614
18.3	Threshold and Smooth-Transition VAR Models	619
18.3.1	Model Setup	619
18.3.2	Example: A TVAR Model of U.S. Monetary Policy	621
18.4	Markov-Switching VAR Models	622
18.4.1	Model Setup	623
18.4.2	Identification	625
18.4.3	Estimation	626
18.4.4	Model Selection	628
18.4.5	Example: An MS-VAR Model of U.S. Monetary Policy	629
18.5	Time-Varying Coefficient VAR Models	630
18.5.1	Model Setup	631
18.5.2	Estimation	633

18.5.3	Example: A TVC-VAR Model of U.S. Monetary Policy	635
18.6	VAR Models with GARCH-in-Mean	636
18.6.1	Model Setup	636
18.6.2	Estimation	637
18.6.3	Example: The Effect of Oil Price Uncertainty on U.S. Real Output	638
18.7	Other Nonlinear Models	640
18.7.1	Nonparametric VAR Analysis	640
18.7.2	Noncausal VAR Models	645
18.8	Discussion of Nonlinear VAR Modeling	648
18.9	Linear Structural Models with Nonlinear Transformations of the Variables	650
18.9.1	The Censored Oil Price VAR Model	651
18.9.2	A Nonlinear Structural Model Allowing for Asymmetric Responses	652
18.9.3	Quantifying Nonlinear Responses to Oil Price Shocks	653
18.9.4	Testing the Null of Unconditionally Symmetric Response Functions	654
18.9.5	Testing the Null of Conditionally Symmetric Response Functions	655
18.9.6	Testing the Null of No Time Dependence	656
18.9.7	Conditional Prediction Error Decompositions	657
18.9.8	Extensions	658
19	Practical Issues Related to Trends, Seasonality, and Structural Change	659
19.1	Alternative Trend Models	659
19.1.1	Hodrick-Prescott (HP) Filter	659
19.1.2	Band-Pass Filters	660
19.1.3	Potential Shortcomings of Trend Filters	661
19.1.4	Trend-Filtered Variables in VAR Models	661
19.1.5	Choosing between Different Trend Models	662
19.1.6	Combining Different Trend Specifications	662
19.2	Seasonality	663
19.2.1	Deterministic Seasonal Variation in VAR Models	663
19.2.2	Stochastic Seasonal Variation in VAR Models	664
19.2.3	Synthesis	666
19.2.4	Periodic Seasonal VAR Models	666
19.2.5	Seasonal TVC-VAR Models	667

16.3	19.2.6 Seasonally Filtered Data in VAR Models	667
16.4	19.2.7 Combining Seasonally Adjusted and Unadjusted Data in the same VAR Model	668
16.4	19.2.8 Summary	668
16.5	19.3 Structural Change in the Stochastic Component of the VAR Model	669
16.5	19.3.1 Breaks in the Stochastic Component	669
16.5	19.3.2 Smooth Structural Change in the Stochastic Component	671
	<i>Bibliography</i>	673
	<i>Notation and Abbreviations</i>	713
	<i>Author Index</i>	721
	<i>Subject Index</i>	729
17.1	17.1.1 A Nonlinear Structural Model	591
17.1	17.1.2 A Nonlinear Representation of Nonlinearity	592
17.1	17.1.3 Breaks in the Stochastic Component	593
17.1	17.1.4 Smooth Structural Change	594
17.1	17.1.5 Other Applications	603
17.2	17.2.1 Conclusions	607
17.3	17.3.1 Testing the Null of No Nonlinearities	609
17.3	17.3.2 Conditionality	609
17.3	17.3.3 Nonlinearity Due to Output Variables	610
17.3	17.3.4 Nonlinearity Due to Input Variables	610
17.3	17.3.5 Nonlinearity Due to Structural Changes	610
17.4	17.4.1 Explanations	611
17.4	17.4.2 Structural Functions	614
17.5	17.5.1 Threshold and Smooth-Transition VAR Models	619
17.5	17.5.1.1 Model Setup	619
17.5	17.5.1.2 Example: A T-VAR	619
17.5	17.5.1.3 Parameter Estimates	621
17.5	17.5.1.4 Forecasting	622
17.5	17.5.1.5 Goodness-of-Fit Measures	623
17.5	17.5.1.6 Comparing Different Trend Specifications	625
17.5	17.5.1.7 Seasonality	626
17.5	17.5.1.8 Deterministic Seasonal Adjustment in VAR Models	628
17.5	17.5.2 Seasonal VAR Models	629
17.5	17.5.2.1 Stochastic Seasonal Variation in VAR Models	630
17.5	17.5.2.2 Summary	631
17.5	17.5.2.3 Periodic Seasonal VAR Models	631
	17.5.2.4 Seasonal T-VAR Models	633