

CAUSALITY

Models, Reasoning, and Inference Second Edition

Judea Pearl

University of California, Los Angeles



CAMBRIDGE
UNIVERSITY PRESS

Contents

<i>Preface to the First Edition</i>	<i>page xv</i>
<i>Preface to the Second Edition</i>	<i>xix</i>
1 Introduction to Probabilities, Graphs, and Causal Models	1
1.1 Introduction to Probability Theory	1
1.1.1 Why Probabilities?	1
1.1.2 Basic Concepts in Probability Theory	2
1.1.3 Combining Predictive and Diagnostic Supports	6
1.1.4 Random Variables and Expectations	8
1.1.5 Conditional Independence and Graphoids	11
1.2 Graphs and Probabilities	12
1.2.1 Graphical Notation and Terminology	12
1.2.2 Bayesian Networks	13
1.2.3 The d -Separation Criterion	16
1.2.4 Inference with Bayesian Networks	20
1.3 Causal Bayesian Networks	21
1.3.1 Causal Networks as Oracles for Interventions	22
1.3.2 Causal Relationships and Their Stability	24
1.4 Functional Causal Models	26
1.4.1 Structural Equations	27
1.4.2 Probabilistic Predictions in Causal Models	30
1.4.3 Interventions and Causal Effects in Functional Models	32
1.4.4 Counterfactuals in Functional Models	33
1.5 Causal versus Statistical Terminology	38
2 A Theory of Inferred Causation	41
2.1 Introduction – The Basic Intuitions	42
2.2 The Causal Discovery Framework	43
2.3 Model Preference (Occam’s Razor)	45
2.4 Stable Distributions	48
2.5 Recovering DAG Structures	49
2.6 Recovering Latent Structures	51

2.7	Local Criteria for Inferring Causal Relations	54
2.8	Nontemporal Causation and Statistical Time	57
2.9	Conclusions	59
2.9.1	On Minimality, Markov, and Stability	61
3	Causal Diagrams and the Identification of Causal Effects	65
3.1	Introduction	66
3.2	Intervention in Markovian Models	68
3.2.1	Graphs as Models of Interventions	68
3.2.2	Interventions as Variables	70
3.2.3	Computing the Effect of Interventions	72
3.2.4	Identification of Causal Quantities	77
3.3	Controlling Confounding Bias	78
3.3.1	The Back-Door Criterion	79
3.3.2	The Front-Door Criterion	81
3.3.3	Example: Smoking and the Genotype Theory	83
3.4	A Calculus of Intervention	85
3.4.1	Preliminary Notation	85
3.4.2	Inference Rules	85
3.4.3	Symbolic Derivation of Causal Effects: An Example	86
3.4.4	Causal Inference by Surrogate Experiments	88
3.5	Graphical Tests of Identifiability	89
3.5.1	Identifying Models	91
3.5.2	Nonidentifying Models	93
3.6	Discussion	94
3.6.1	Qualifications and Extensions	94
3.6.2	Diagrams as a Mathematical Language	96
3.6.3	Translation from Graphs to Potential Outcomes	98
3.6.4	Relations to Robins's <i>G</i> -Estimation	102
4	Actions, Plans, and Direct Effects	107
4.1	Introduction	108
4.1.1	Actions, Acts, and Probabilities	108
4.1.2	Actions in Decision Analysis	110
4.1.3	Actions and Counterfactuals	112
4.2	Conditional Actions and Stochastic Policies	113
4.3	When Is the Effect of an Action Identifiable?	114
4.3.1	Graphical Conditions for Identification	114
4.3.2	Remarks on Efficiency	116
4.3.3	Deriving a Closed-Form Expression for Control Queries	117
4.3.4	Summary	118
4.4	The Identification of Dynamic Plans	118
4.4.1	Motivation	118
4.4.2	Plan Identification: Notation and Assumptions	120

4.4.3	Plan Identification: The Sequential Back-Door Criterion	121
4.4.4	Plan Identification: A Procedure	124
4.5	Direct and Indirect Effects	126
4.5.1	Direct versus Total Effects	126
4.5.2	Direct Effects, Definition, and Identification	127
4.5.3	Example: Sex Discrimination in College Admission	128
4.5.4	Natural Direct Effects	130
4.5.5	Indirect Effects and the Mediation Formula	132
5	Causality and Structural Models in Social Science and Economics	133
5.1	Introduction	134
5.1.1	Causality in Search of a Language	134
5.1.2	SEM: How Its Meaning Became Obscured	135
5.1.3	Graphs as a Mathematical Language	138
5.2	Graphs and Model Testing	140
5.2.1	The Testable Implications of Structural Models	140
5.2.2	Testing the Testable	144
5.2.3	Model Equivalence	145
5.3	Graphs and Identifiability	149
5.3.1	Parameter Identification in Linear Models	149
5.3.2	Comparison to Nonparametric Identification	154
5.3.3	Causal Effects: The Interventional Interpretation of Structural Equation Models	157
5.4	Some Conceptual Underpinnings	159
5.4.1	What Do Structural Parameters Really Mean?	159
5.4.2	Interpretation of Effect Decomposition	163
5.4.3	Exogeneity, Superexogeneity, and Other Frills	165
5.5	Conclusion	170
5.6	Postscript for the Second Edition	171
5.6.1	An Econometric Awakening?	171
5.6.2	Identification in Linear Models	171
5.6.3	Robustness of Causal Claims	172
6	Simpson's Paradox, Confounding, and Collapsibility	173
6.1	Simpson's Paradox: An Anatomy	174
6.1.1	A Tale of a Non-Paradox	174
6.1.2	A Tale of Statistical Agony	175
6.1.3	Causality versus Exchangeability	177
6.1.4	A Paradox Resolved (Or: What Kind of Machine Is Man?)	180
6.2	Why There Is No Statistical Test for Confounding, Why Many Think There Is, and Why They Are Almost Right	182
6.2.1	Introduction	182
6.2.2	Causal and Associational Definitions	184
6.3	How the Associational Criterion Fails	185
6.3.1	Failing Sufficiency via Marginality	185
6.3.2	Failing Sufficiency via Closed-World Assumptions	186

6.3.3	Failing Necessity via Barren Proxies	186
6.3.4	Failing Necessity via Incidental Cancellations	188
6.4	Stable versus Incidental Unbiasedness	189
6.4.1	Motivation	189
6.4.2	Formal Definitions	191
6.4.3	Operational Test for Stable No-Confounding	192
6.5	Confounding, Collapsibility, and Exchangeability	193
6.5.1	Confounding and Collapsibility	193
6.5.2	Confounding versus Confounders	194
6.5.3	Exchangeability versus Structural Analysis of Confounding	196
6.6	Conclusions	199
7	The Logic of Structure-Based Counterfactuals	201
7.1	Structural Model Semantics	202
7.1.1	Definitions: Causal Models, Actions, and Counterfactuals	202
7.1.2	Evaluating Counterfactuals: Deterministic Analysis	207
7.1.3	Evaluating Counterfactuals: Probabilistic Analysis	212
7.1.4	The Twin Network Method	213
7.2	Applications and Interpretation of Structural Models	215
7.2.1	Policy Analysis in Linear Econometric Models: An Example	215
7.2.2	The Empirical Content of Counterfactuals	217
7.2.3	Causal Explanations, Utterances, and Their Interpretation	221
7.2.4	From Mechanisms to Actions to Causation	223
7.2.5	Simon's Causal Ordering	226
7.3	Axiomatic Characterization	228
7.3.1	The Axioms of Structural Counterfactuals	228
7.3.2	Causal Effects from Counterfactual Logic: An Example	231
7.3.3	Axioms of Causal Relevance	234
7.4	Structural and Similarity-Based Counterfactuals	238
7.4.1	Relations to Lewis's Counterfactuals	238
7.4.2	Axiomatic Comparison	240
7.4.3	Imaging versus Conditioning	242
7.4.4	Relations to the Neyman–Rubin Framework	243
7.4.5	Exogeneity and Instruments: Counterfactual and Graphical Definitions	245
7.5	Structural versus Probabilistic Causality	249
7.5.1	The Reliance on Temporal Ordering	249
7.5.2	The Perils of Circularity	250
7.5.3	Challenging the Closed-World Assumption, with Children	252
7.5.4	Singular versus General Causes	253
7.5.5	Summary	256
8	Imperfect Experiments: Bounding Effects and Counterfactuals	259
8.1	Introduction	259
8.1.1	Imperfect and Indirect Experiments	259
8.1.2	Noncompliance and Intent to Treat	261

8.2	Bounding Causal Effects with Instrumental Variables	262
8.2.1	Problem Formulation: Constrained Optimization	262
8.2.2	Canonical Partitions: The Evolution of Finite-Response Variables	263
8.2.3	Linear Programming Formulation	266
8.2.4	The Natural Bounds	268
8.2.5	Effect of Treatment on the Treated (ETT)	269
8.2.6	Example: The Effect of Cholestyramine	270
8.3	Counterfactuals and Legal Responsibility	271
8.4	A Test for Instruments	274
8.5	A Bayesian Approach to Noncompliance	275
8.5.1	Bayesian Methods and Gibbs Sampling	275
8.5.2	The Effects of Sample Size and Prior Distribution	277
8.5.3	Causal Effects from Clinical Data with Imperfect Compliance	277
8.5.4	Bayesian Estimate of Single-Event Causation	280
8.6	Conclusion	281
9	Probability of Causation: Interpretation and Identification	283
9.1	Introduction	283
9.2	Necessary and Sufficient Causes: Conditions of Identification	286
9.2.1	Definitions, Notation, and Basic Relationships	286
9.2.2	Bounds and Basic Relationships under Exogeneity	289
9.2.3	Identifiability under Monotonicity and Exogeneity	291
9.2.4	Identifiability under Monotonicity and Nonexogeneity	293
9.3	Examples and Applications	296
9.3.1	Example 1: Betting against a Fair Coin	296
9.3.2	Example 2: The Firing Squad	297
9.3.3	Example 3: The Effect of Radiation on Leukemia	299
9.3.4	Example 4: Legal Responsibility from Experimental and Nonexperimental Data	302
9.3.5	Summary of Results	303
9.4	Identification in Nonmonotonic Models	304
9.5	Conclusions	307
10	The Actual Cause	309
10.1	Introduction: The Insufficiency of Necessary Causation	309
10.1.1	Singular Causes Revisited	309
10.1.2	Preemption and the Role of Structural Information	311
10.1.3	Overdetermination and Quasi-Dependence	313
10.1.4	Mackie's INUS Condition	313
10.2	Production, Dependence, and Sustenance	316
10.3	Causal Beams and Sustenance-Based Causation	318
10.3.1	Causal Beams: Definitions and Implications	318
10.3.2	Examples: From Disjunction to General Formulas	320
10.3.3	Beams, Preemption, and the Probability of Single-Event Causation	322

10.3.4	Path-Switching Causation	324
10.3.5	Temporal Preemption	325
10.4	Conclusions	327
11	Reflections, Elaborations, and Discussions with Readers	331
11.1	Causal, Statistical, and Graphical Vocabulary	331
11.1.1	Is the Causal-Statistical Dichotomy Necessary?	331
11.1.2	d -Separation without Tears (Chapter 1, pp. 16–18)	335
11.2	Reversing Statistical Time (Chapter 2, p. 58–59)	337
11.3	Estimating Causal Effects	338
11.3.1	The Intuition behind the Back-Door Criterion (Chapter 3, p. 79)	338
11.3.2	Demystifying “Strong Ignorability”	341
11.3.3	Alternative Proof of the Back-Door Criterion	344
11.3.4	Data vs. Knowledge in Covariate Selection	346
11.3.5	Understanding Propensity Scores	348
11.3.6	The Intuition behind do -Calculus	352
11.3.7	The Validity of G -Estimation	352
11.4	Policy Evaluation and the do -Operator	354
11.4.1	Identifying Conditional Plans (Section 4.2, p. 113)	354
11.4.2	The Meaning of Indirect Effects	355
11.4.3	Can $do(x)$ Represent Practical Experiments?	358
11.4.4	Is the $do(x)$ Operator Universal?	359
11.4.5	Causation without Manipulation!!!	361
11.4.6	Hunting Causes with Cartwright	362
11.4.7	The Illusion of Nonmodularity	364
11.5	Causal Analysis in Linear Structural Models	366
11.5.1	General Criterion for Parameter Identification (Chapter 5, pp. 149–54)	366
11.5.2	The Causal Interpretation of Structural Coefficients	366
11.5.3	Defending the Causal Interpretation of SEM (or, SEM Survival Kit)	368
11.5.4	Where Is Economic Modeling Today? – Courting Causes with Heckman	374
11.5.5	External Variation versus Surgery	376
11.6	Decisions and Confounding (Chapter 6)	380
11.6.1	Simpson’s Paradox and Decision Trees	380
11.6.2	Is Chronological Information Sufficient for Decision Trees?	382
11.6.3	Lindley on Causality, Decision Trees, and Bayesianism	384
11.6.4	Why Isn’t Confounding a Statistical Concept?	387
11.7	The Calculus of Counterfactuals	389
11.7.1	Counterfactuals in Linear Systems	389
11.7.2	The Meaning of Counterfactuals	391
11.7.3	d -Separation of Counterfactuals	393

Contents	xiii
11.8 Instrumental Variables and Noncompliance	395
11.8.1 Tight Bounds under Noncompliance	395
11.9 More on Probabilities of Causation	396
11.9.1 Is “Guilty with Probability One” Ever Possible?	396
11.9.2 Tightening the Bounds on Probabilities of Causation	398
Epilogue The Art and Science of Cause and Effect	
A public lecture delivered in November 1996 as part of the UCLA Faculty Research Lectureship Program	401
<i>Bibliography</i>	429
<i>Name Index</i>	453
<i>Subject Index</i>	459