

JUDEA PEARL
WINNER OF THE TURING AWARD
AND DANA MACKENZIE

THE
BOOK OF
WHY



THE NEW SCIENCE
OF CAUSE AND EFFECT

INDEX

- Abbott, Robert, 141, 143
abduction, 278, 280
ACE. *See average causal effect*
acquisition, representation and, 38
action, in counterfactuals, 278, 280
agency, 367
AI. *See artificial intelligence*
Allen, Myles, 291–294
American Cancer Society, 174,
 178–179
anthropometric statistics, 58
Aristotle, 50, 264
artificial intelligence (AI), ix–x, 10
 Bayesian networks in, 18, 93–94,
 108–109, 112, 132
 message-passing network of,
 110–111, 111 (fig.)
 of robots, 291
 Turing on, 27, 108–109
uncertainty in, 109
weak, 362
“why?” question in, 349
 See also strong AI
Asimov, Isaac, 370
association, 50, 340
 causation and, 181, 189
 in Ladder of Causation, 28 (fig.),
 29–30, 51
 pattern of, 311
 specificity, strength of, 181
 See also correlation, genome-wide
 association study
assumptions, 12–13, 12 (fig.)
astronomy, 5
attribution, 261, 291, 293, 393–394
average causal effect (ACE), 296–297
backdoor adjustment formula,
 220–224
backdoor criterion
 and causal effects, 220, 225–226
 confounding and, 157, 219
 in *do*-calculus, 234
 do-operator and, 157–165, 330
backdoor path, 158–159
background factors, 48
Bareinboim, Elias, 239, 353, 356–358
Baron, Reuben, 324–325, 339
Bayes, Thomas, 95–96, 96 (fig.), 264
 on data, 100, 102
 on inverse probability, 97–99, 98
 (fig.), 101, 104–105, 112–113
 method of, 99–100
 on miracles, 103
 on probability, 97–98, 102
 and subjectivity, 90, 104, 108
Bayesian analysis, 194–195
Bayesian conditioning, 194
Bayesian networks, 50–51, 81,
 92 (photo)
 in AI, 18, 93–94, 108–109, 112, 132
 in Bonaparte software, 95
 causal diagrams and, 128–133
 codewords, turbo codes in, 126,
 127 (fig.) 128
 conditional probability table in,
 117, 119, 120 (table)
 DNA tests and, 122, 123 (fig.), 124

- Bayesian networks (*continued*)
 inverse-probability problem in, 112–113, 119–120
 junctions in, 113–116
 in machine learning, 125
 parent nodes in, 117
 probability in, 358–359
 probability tables in, 128–129
 SCMs versus, 284
- Bayesian statistics, 89–91
- Bayes's rule, 101–104, 196
- BCSC. *See* Breast Cancer Surveillance Consortium
- belief, 101–102
- belief propagation, 112–113, 128
- Berkeley admission paradox, 197–198
- Berkson, Joseph, 197–200, 197 (fig.), 198 (table)
- Bernoulli, Jacob, 5
- Berrou, Claude, 126–127
- Bickel, Peter, 310–312, 315–316
- Big Data, 3, 350–358, 354 (fig.)
- birth weight, 82–83, 82 (fig.)
- birth-weight paradox, 185–186, 185 (fig.), 189
- black box analysis, 125, 283
- Blalock, Hubert, 309, 326
- Bonaparte, 94–95, 122, 123 (fig.), 124–125
- brain
 managing causes, effects, 2
 representation, of information in, 39
See also human mind
- Breast Cancer Surveillance Consortium (BCSC), 105–106, 107 (fig.), 118
- Brito, Carlos, 257
- Brockman, John, 367–368
- Brown, Lisa, 216, 217 (fig.)
- Burks, Barbara, 198, 304, 311, 333
 on nature-versus-nurture debate, 305–306, 305 (fig.), 306 (fig.)
 path diagram of, 308–309
 on social status, 307
- but-for causation, 261–263, 286–288
- canned procedures, 84–85
- Cartwright, Nancy, 49
- case studies. *See* examples
- case-control studies, 173
- Castle, William, 72–73
- causal analysis
 data in, 85
 subjectivity and, 89
- causal diagram, 7, 39–40, 39 (fig.), 41–42, 41 (fig.), 118 (fig.), 142 (fig.)
 for “Algebra for All,” 337, 338 (fig.)
- Bayesian network and, 128–133
- for Berkeley admission paradox, 311–312, 312 (fig.), 314 (fig.)
- for Berkson’s paradox, 197 (fig.)
- for birth-weight paradox, 185, 185 (fig.)
- for cholera, 247–248, 247 (fig.), 248 (fig.)
- for climate change, 294, 294 (fig.)
- confounder in, 138, 138 (fig.), 140
- of counterfactual, 42–43, 42 (fig.)
- direct effect in, 320–321
- do*-operator in, 148 (fig.)
- front-door adjustment in, 225 (fig.)
- of Galton board, 64–65, 64 (fig.)
- of genetic model, 64–65, 64 (fig.)
- graphical structure of, 131
- for improperly controlled experiment, 147–148, 147 (fig.)
- instrumental variables and, 250
- of JTPA Study, 229–231, 230 (fig.)
- for Lord’s paradox, 214, 215 (fig.)
- for Mendelian randomization, 255–256, 256 (fig.)
- for Monty Hall paradox, 193–194, 193 (fig.), 195 (fig.)
- of napkin problem, 239–240, 240 (fig.)
- of nature-versus-nurture debate, 305, 305 (fig.)
- noncausal path in, 157, 160
- for RCT, with noncompliance, 252–253, 253 (fig.)

- RCT in, 140, 148–149, 149 (fig.)
of Simpson's paradox, 206–207,
206 (fig.), 209 (fig.)
for smoking gene example, 341,
341 (fig.), 342 (fig.)
supply-side, 250–251, 251 (fig.)
for tourniquet example, 346,
346 (fig.)
of vaccination, 44–46, 45 (fig.)
See also path diagram
- causal effect
backdoor criterion for, 220,
225–226
through path coefficients, 77
through regression coefficients,
222–223
- causal inference
cause, effect in, 2–3
human mind and, 1–2, 43
mathematical language of, 3–8
objectivity of, 91
by robots, 2, 350, 361, 361 (fig.)
in statistics, 18
technology of, 1–2
- causal inference engine, 11–15,
12 (fig.), 26–27, 46
- causal knowledge, of machines, 37
- causal model, 12 (fig.), 13, 16–17,
45–46
Big Data and, 350–358, 354 (fig.)
as hypothetical experiments, 130
doing in, 27
imagining in, 27
mediation in, 300–301
seeing vs. doing, 27
of Rubin, 261, 280–281
testing of, 116
See also linear causal model;
structural causal model
- causal paradoxes, 189–190
- causal questions, language of, 5
- causal reasoning, 20–21, 43
- the Causal Revolution, ix–x, 7, 9, 11,
45, 140, 301, 350
- causal subjectivity, 90
- causal vocabulary, 5
- causality, ix
provisional, 150
queries of, 27, 183
statistics and, 66, 190
- Causality* (Pearl), ix, 24, 328, 331
- causation
association and, 181, 189
computers understanding, 40–41
correlation and, 5–6, 82–84
intuition about, 321
necessary, 289–290
Pearson, K., and, 71–72
probability and, 47–51
RCT for, 169
repetition and, 66–67
smoking-cancer debate in, 168
in statistics, 18
three levels of, 27–36
Wright, S., on, 79–81
See also Ladder of Causation
- cause
defining, 47–48, 179–180
proximate, 288–289
sufficient and necessary, 288–291,
295
See also common cause principle
- causes, effects and, 2–3
in causal diagrams, 187
probability versus, 46
- c-decomposition, 243
- Cerf, Vint, 95
- child nodes, 111–112, 129
- Chinese Room argument, 38–39
- cholera, 168
See also examples
- climate change
causal diagram of, 294, 294 (fig.)
computer simulation of, 292–296
counterfactuals and, 261–262, 295
FAR and, 291–292
See also examples
- Cochran, William, 180, 182
- codewords, 126, 127 (fig.), 128
- coefficients
difference in, 327
path, 77, 223, 251
product of, 327
regression, 222–223

- Cognitive Revolution, 24–25, 34–35
 coherence, 181–182
 collider bias, 185–186, 197–200
 common cause principle, 199
 compatibilists, 364
 completeness, 237, 243–244
 computer simulation, in climate science, 292–296
 computers
 causation and, 40–41
 counterfactuals and, 43
 “Computing Machinery and Intelligence” (Turing), 358
 conditional probability, 101, 103
 conditional probability table, 117 (table), 119, 120 (table)
 confounders, 137, 138 (fig.), 140
 of mediator, outcome, 315–316
 mediators and, 276
 provisional conclusions and, 143
 RCT and, 149–150
 in smoking risk, 175
 in statistics, 138–139, 141–142
 See also deconfounders
 confounding
 backdoor criterion for, 157, 219
 classical epidemiological definition of, 153–154, 159
 defining, 150–151, 156, 162
 in epidemiology, 152–154
 incomparability in, 151
 indirect, 241
 in Ladder of Causation, 140
 statistics and, 141, 151, 156
 surrogates in, 152
 third-variable definition, 151–152
 confounding bias, 137–138, 147
 Conrady, Stefan, 118–119
 consistency, 181, 281
 controlled experiment, 136–137, 147 (fig.)
 See also experimental design; randomized controlled trial
 Cornfield, Jerome, 175, 179–180, 183, 224, 341
 Cornfield’s inequality, 175
 Coronary Primary Prevention Trial, 252
 correlation, 29
 causation and, 5–6, 82–84
 Galton on, 62–63
 spurious, 69–72
 See also association, collider bias
 “Correlation and Causation” (Wright, S.), 82
 counterfactual analysis, 261–262
 counterfactuals, 9–10
 causal diagram for, 42–43, 42 (fig.)
 climate change and, 261–262, 295
 computers and, 43
 data and, 33
 do-expression of, 287–288
 exchangeability and, 154–155
 Frost and, 258 (photo)
 in human mind, 33
 Hume and, 19–20, 265–267
 indirect effects and, 322
 in inference engine, 296
 in Ladder of Causation, 266
 law and, 286–291
 Lewis on, 266–269
 mediation analysis for, 297
 and possible worlds, 266–269
 queries as, 20, 28 (fig.), 36, 260–261, 284
 reasoning, 10
 SCMs for, 276–280, 283–284
 for strong AI, 269
 Cox, David, 154, 240–241, 241 (fig.)
 Crow, James, 84–85
 culpability, 261
 curse of dimensionality, 221
 Curve of Abandoning Hope, 120–121
 d-separation, 116, 242, 283, 381
 Darwiche, Adnan, 30
 Darwin, Charles, 63, 73, 87
 data, 11, 12 (fig.), 14–16
 Bayes on, 100, 102
 in causal analysis, 85
 counterfactuals and, 33
 economists and, 86
 fusion, 355
 interpretation, 352
 in machine learning, 30–31
 methods and, 84–85

- mining, 351–352
objectivity of, 89
Pearson, K., on, 87–88
reduction of, 85
in science, 6, 84–85
See also Big Data
- David, Richard, 187
- Dawid, Phillip, 237, 350
- de Fermat, Pierre, 4–5
- de Moivre, Abraham, 5
- death, proximate cause of, 288
- decision problem, 238–239
- decoding, 125–126, 127 (fig.), 128
- deconfounders, 139–140
- back-door paths for, 158–159
 in intervention, 220
- deconfounding games, 159–165
- deduction, induction and, 93
- deep learning, 3, 30, 359, 362
- Democritus, 34
- The Design of Experiments* (Cox), 154
- developmental factors, of guinea pigs, 74–76, 75 (fig.)
- Dewar, James, 53
- Diaconis, Persi, 196
- difference, in coefficients, 327
- direct effect, 297, 300–301, 317–318
- in causal diagram, 320–321
- of intervention, 323–324
- in mediation formula, 333
- mediators and, 326, 332
- See also* indirect effects; natural direct effect
- The Direction of Time* (Reichenbach), 199
- discrimination, 311–312, 315–316
- DNA test, 94–95, 122, 123 (fig.), 124, 342
- do*-calculus, 241–242
- backdoor criterion in, 234
- completeness of, 243–244
- decision problem in, 238–239
- elimination procedure in, 231–232
- front-door adjustment in, 235–237, 236 (fig.)
- instrumental variables in, 257
- transformations in, 233–234, 238
- transparency in, 239–240
- as universal mapping tool, 219–220
- do*-expression, 8, 32, 49, 287–288
- Doll, Richard, 171–174, 172 (fig.)
- do*-operator, 8–9, 49, 147–148, 148 (fig.), 151
- backdoor criterion and, 157–165, 330
- elimination procedure for, 237
- for intervention, 231
- in noncausal paths, 157
- do*-probabilities, 226
- Duncan, Arne, 336
- Duncan, Otis, 285, 309, 326
- economics, path analysis in, 79, 84, 86, 236, 244, 250, 285, 362, 376
- effects of treatment on the treated (ETT), 296–297
- elimination procedure, 231–232, 237
- Ellenberg, Jordan, 200
- Elwert, Felix, 115
- An Enquiry Concerning Human Understanding* (Hume), 265–266
- epidemiology, 169
- admission rate bias in, 197–198
- confounding in, 152–154
- mediation fallacy in, 315–316
- RCT in, 172–173
- Robins in, 329 (fig.)
- equation deletion, 244
- Erdos, Paul, 196
- error-correcting code, 126
- estimand, 12 (fig.), 14–15, 17
- estimate, 12 (fig.), 15
- ETT. *See* effects of treatment on the treated
- Euclidean geometry, 48, 101, 233
- evolution, human, 23–26
- examples
- Abraham and fifty righteous men, 263–264, 283–284
- “Algebra for All,” 301, 336–339, 338 (fig.)
- AlphaGo, 359–362
- aspirin and headache, 33, 267

- examples (*continued*)
 attractive men are jerks, 200
 bag on plane, 118–121, 118 (fig.)
 Bayes's billiard ball, 98–99,
 98 (fig.), 104, 108
 Berkeley admissions and
 discrimination, 309–316,
 312 (fig.), 314 (fig.), 317–318
 Berkson's paradox, 197–200, 197
 (fig.), 198 (table)
 birth weight in guinea pigs, 82–83,
 82 (fig.)
 blocked fire escape, 286–291
 chocolate and Nobel Prize
 winners, 69
 cholera, 245–249, 247 (fig.),
 248 (fig.)
 coat color in guinea pigs, 72–76,
 74 (fig.), 75 (fig.)
 coin flip experiment, 199–200
 Daisy and kittens, 319–322,
 320 (fig.)
 Daniel and vegetarian diet,
 134 (photo), 135–137
 education, skill and salary, 325–326
 falling piano, 288–289
 fertilizer and crop yield, 145–149
 fire, smoke, and alarm, 113–114
 firing squad, 39–43, 39 (fig.)
 flaxseed, elasticity of supply,
 250–251, 251 (fig.)
 flu vaccine, 155–156, 156 (table)
 Galton board, 52 (photo), 54–55,
 56–57, 57 (fig.), 63–65, 64 (fig.)
 Garden of Eden, 23–25
 HDL cholesterol and heart attack,
 254–257
 ice cream and crime rates, 48
 inheritance of stature, 55–60,
 59 (fig.)
 intelligence, nature versus nurture,
 304–309
 job training and earnings, 228–231
 LDL cholesterol, 252–257,
 254 (table)
Let's Make a Deal, 192–196,
 195 (fig.)
 Lord's paradox: diet and weight
 gain, 215–217, 215 (fig.),
 217 (fig.)
 Lord's paradox: gender and
 weight gain, 212–215, 213 (fig.)
 mammogram and cancer risk,
 104–108
 mammoth hunt, 25–26, 26 (fig.)
 matches or oxygen as cause of fire,
 289–290
 Monty Hall paradox, 188 (photo),
 189–197, 191 (table), 193 (fig.),
 193 (table), 195 (fig.), 200
 mortality rate and Anglican
 weddings, 70
 online advertising, 354–355
 robot soccer, 365–366
 salary, education, and experience,
 272–283, 273 (table), 276 (fig.)
 scurvy and Scott expedition,
 298 (photo), 299–300, 302–304,
 303 (fig.)
 shoe size, age, and reading ability,
 114–115
 Simpson's paradox: BBG drug,
 189, 200–204, 201 (table),
 206–210, 206 (fig.), 208 (table),
 209 (fig.), 221
 Simpson's paradox: exercise and
 cholesterol, 211–212, 212 (fig.)
 Simpson's paradox: kidney stones,
 210
 Simpson's paradox: smoking and
 thyroid disease, 210
 Simpson's reversal: batting
 averages, 203–204, 203 (table),
 211
 skull length and breadth, 70–71,
 70 (fig.)
 smoking, birth weight, and infant
 mortality, 183–187, 185 (fig.)
 smoking, tar, and cancer, 224–228,
 297
 smoking and adult asthma, 164,
 164 (fig.)
 smoking and lung cancer, 18–19,
 167–179, 172 (fig.), 176 (fig.)

- smoking and miscarriages, 162–163
smoking gene, 339–343, 341 (fig.), 342 (fig.)
sure-thing principle, 204–206, 316
talent, success, and beauty, 115–116
tea and scones, 99–102, 100 (table), 104–105, 112–113
toothpaste and dental floss, 29–30, 32, 34
tourniquets, 343–347, 345 (table), 346 (fig.)
tsunami at Orobiae, 262–263, 266
turbo codes, 125–126, 127 (fig.), 128
2003 heat wave and climate change, 292–296, 294 (fig.)
vaccination and smallpox, 43–44, 45 (fig.)
victim DNA identification, 94–95
walking and death rate, 141–143, 142 (fig.)
exchangeability, 154–156, 162, 181
experimental design, 145–146, 146 (fig.)
external validity, 357
- Facebook, 32, 351
false positives, 106–107, 107 (fig.)
false negatives, 107 (fig.)
FAR. *See* fraction of attributable risk
Faraday, Michael, 53
Feigenbaum, Edward, 109
feminism, 67–68
Fieser, Louis, 182
Fisher, R. A., 169, 224, 271–272
experimental design of, 145–146, 146 (fig.)
Neyman, J., and, 271–272
on RCT, 139–140, 143–144
on smoking gene, 174–175
in smoking-cancer debate, 178–179
on statistics, 85
Wright, S., and, 85
Fisher Box, Joan, 144–145, 149
Forbes, Andrew, 163–164, 164 (fig.)
formulas, 334–335
forward probability, 104, 112–113
fraction of attributable risk (FAR), 291–292
free will, 358–370
Freedman, David, 227–228, 236, 285
front-door adjustment, 225 (fig.), 235–237, 236 (fig.)
front-door criterion, 224–231, 225 (fig.), 229 (fig.)
Frost, Robert, 258 (photo)
- Galileo, 81, 187
Gallagher, Robert, 128
Galton, Francis, 3, 5, 52 (photo), 53, 78
anthropometric statistics of, 58
on correlation, 62–63
on eminence, 56
Hereditary Genius by, 55–56
Natural Inheritance by, 66
Pearson, K., and, 66–68
on regression to the mean, 57–58, 67
on regression line, 60–62, 61 (fig.), 221–222
“Typical Laws of Heredity” by, 54
See also examples
games, deconfounding, 159–165
Gauss, Carl Friedrich, 5
Geiger, Dan, 242–243, 245, 285
Genesis, 23–25, 263
genetic modeling, 64–65, 64 (fig.)
genetics. *See* DNA test; examples; Mendelian genetics
genome-wide association study (GWAS), 339–340
geometry, 232–233
Glymour, Clark, 350
Glynn, Adam, 228–230
God, 23–24
Goldberger, Arthur, 84–85
graphoids, 381
Greek logic, 232

- Greenland, Sander, 150, 154–156, 168, 237, 333–334
See also Robins, Jamie
- guilt, probability of, 288
- guinea pigs. *See* examples
- GWAS. *See* genome-wide association study
- Haavelmo, Trygve, 285
- Hagenaars, Jacques, 331
- Halley, Edmond, 5
- Halpern, Joseph, 350
- Hammel, Eugene, 309–311
- Hannart, Alexis, 294–295
- Harari, Yuval, 25, 34
- Hardy, G. H., 65
- HDL. *See* high-density lipoprotein cholesterol
- Heckman, James, 236
- Hereditary Genius* (Galton), 55–56
- Hernberg, Sven, 152
- high-density lipoprotein (HDL) cholesterol, 254–257
- Hill, Austin Bradford, 169–170, 172–174, 172 (fig.), 181
- Hill's criteria, 181–183
- Hipparchus, 232
- A History of Epidemiologic Methods and Concepts* (Morabia), 152–153
- History of the Peloponnesian War* (Thucydides), 262
- Hitchcock, Christopher, 350
- Holland, Paul, 236, 273, 275
- Hooke's Law, 33
- Hong, Guanglei, 337–338
- How Not to Be Wrong* (Ellenberg), 200
- human
- cognition, 99
 - communicating, with robot, 366
 - evolution, 23–26
- human mind
- causal inference of, 1–2, 43
 - counterfactuals in, 33
- humanlike intelligence, 30, 269
- Hume, David, 103
- on counterfactuals, 19–20, 265–267
 - An Enquiry Concerning Human Understanding* by, 265–266
 - "On Miracles" by, 96–97
 - Treatise of Human Nature* by, 264–265, 265 (fig.)
- Huygens, Christiaan, 4–5
- hypothetical experiments, 130
- ignorability, 281–282
- imagination
- in causation, 27
 - the Lion Man as, 34–35
 - in mental model, 26, 26 (fig.)
- imitation game, 36–37
- incomparability, 151
- indirect confounding, 241
- indirect effects
- counterfactuals and, 322
 - in mediation analysis, 297, 300–301
 - as product, 328–329
 - See also* natural indirect effect
- induction, deduction and, 93
- inference engine, 296, 352
- See also* causal inference engine
- information
- flow of, 157–158
 - representing, in brain, 97
 - transfer of, 194
- instrumental variables, 249–250, 249 (fig.), 257
- intention, 367
- intervention, 9, 131, 150
- deconfounders in, 220
 - direct effect of, 323–324
 - do*-operator for, 149–150, 231
 - in Ladder of Causation, 28 (fig.), 31–33, 40, 219, 231
 - prediction and, 32
 - variables in, 257
 - See also* Mount Intervention
- intuition, 47, 99, 125, 189, 321

- inverse probability
Bayes on, 97–99, 98 (fig.), 101, 104–105
in Bayesian network, 112–113, 119–120
likelihood ratio and, 105, 113
- Jeffreys, Harold, 103
- Jeter, Derek, 203, 203 (table)
- Job Training Partnership Act (JTPA)
Study, 228–231, 229 (fig.), 230 (fig.)
- Joffe, Marshall, 283
- Jouffe, Lionel, 118–119
- JTPA. *See* Job Training Partnership Act Study
- junctions
in Bayesian networks, 113–116
in flow, of information, 157–158
- Justice, David, 203, 203 (table)
- Kahneman, Daniel, 58, 63–64, 290
- Karl Pearson* (Porter), 67
- Karlin, Samuel, 87
- Kashin, Konstantin, 228–230
- Kathiresan, Sekar, 256
- Ke Jie, 360
- Kempthorne, Oscar, 272
- Kenny, David, 324–325, 339
- Klein, Ezra, 139, 154
- knowledge, 8, 11–12, 12 (fig.)
- Koettlitz, Reginald, 302–304
- Kragh, John, 343–347
- Kruskal, William, 312–316, 346
- Ladder of Causation, 17–19, 24, 116
association in, 28 (fig.), 29–30, 51
bias in, 311
confounding in, 140
counterfactuals in, 266
intervention in, 28 (fig.), 31–33, 40, 219, 231
model-free approach to, 88
observation in, 264
probabilities and, 47–49, 75
queries in, 28 (fig.), 29, 32
- language
of knowledge, 8
mathematical, 3–8
of probability, 102–103
of queries, 8, 10
- Laplace, Pierre-Simon, 5
- Latin square, 145, 146 (fig.)
- law, counterfactuals and, 286–291
- LDL. *See* low-density lipoprotein cholesterol
- Let's Make a Deal*. *See* examples
- Lewis, David, 20, 266–269
- likelihood ratio, 105–106, 113
- Lilienfeld, Abe, 175, 179–180
- Lind, James, 168, 299, 302–303
- Lindley, Dennis, 209
- linear causal model, 322–323, 327
- linear models, 295–296
- linear regression, 285–286
- linear SCMs, 285–286
- the Lion Man, 34–36, 35 (fig.)
- LISREL, 86
- logic, 232, 238
- Lord's paradox. *See* examples
- low-density lipoprotein (LDL)
cholesterol, 252–257, 254 (table)
- lung cancer, smoking in, 18–19, 167–168
- machine learning, 10–11, 30–31, 125, 363
See also artificial intelligence (AI)
- machines
causal knowledge of, 37
thinking, 367–368
See also robots
- MacKay, David, 127–128
- Malaysia Airlines crash, 122, 123 (fig.)
- Marcus, Gary, 30
- matching, 274
- mathematical certainty, 288
- mathematical language, 3–8
- mathematics, science and, 4–5, 84–85
See also geometry
- M-bias, 161
- McDonald, Rod, 325

- mediation, 20
 "Algebra for All" as, 336–339, 338 (fig.)
 analysis, 297, 300–301, 322–323
 in causation, 300–301
 fallacy, 272, 315–316
 formula, 319, 332–333, 335
 questions, 131
 smoking gene example as, 339–343, 341 (fig.), 342 (fig.)
 threshold effect and, 325, 326 (fig.)
- mediators, 153–154, 228, 297
 confounders and, 276
 direct effect and, 326, 332
 outcomes and, 315–316
- Mendel, Gregor, 65
- Mendelian genetics, 73
- Mendelian randomization, 255–256, 256 (fig.)
- mental model, 26, 26 (fig.)
- message-passing network, 110–111, 111 (fig.)
- methods, data and, 84–85
- mini-Turing test, 36–46
- miracles, 103, 357
- model discovery, 373
- model-blind, 33, 66, 132, 217, 275
- Model Penal Code, 286, 288
- model-free approach, 87–89, 272, 351
- See also* model-blind
- Morabia, Alfredo, 152–153
- Mount Intervention, 218 (photo), 219–220, 224, 259–260
- Musk, Elon, 367
- napkin problem, 239–240, 240 (fig.), 330
- natural direct effect (NDE), 318–319, 332–333
- natural effects, 327
- natural indirect effect (NIE), 319, 321, 325–326, 332–333
- Natural Inheritance* (Galton), 66
- nature, 144–145, 147, 149, 156, 257
- nature-versus-nurture debate, 304–309, 305 (fig.), 306 (fig.)
- NDE. *See* natural direct effect
- necessary causation, 289–290, 295
- necessity, probability of, 294
- Netherlands Forensic Institute (NFI), 94, 122, 125
- Neyman, Jerzy, 85, 261, 270–272
- NFI. *See* Netherlands Forensic Institute
- NIE. *See* natural indirect effect
- Niles, Henry, 78–81, 84
- noncausal path, in causal diagram, 157, 160
- noncollapsibility, 152
- noncompliance, RCT with, 252–253, 253 (fig.)
- nonconfoundedness, 281
- nonlinear analysis, 335
- nonrandomized studies, 149
- Novick, Melvin, 201, 209
- objectivity
 in Bayesian inference, 89
 of causal inference, 91
- observational studies, 150–151, 229
- Ogburn, William Fielding, 309
- "On Miracles" (Hume), 96–97
- "On the Inadequacy of the Partial and Multiple Correlation Technique" (Burks), 308
- Origin of Species* (Darwin), 63
- paradox, 9, 19, 189–190
 birth-weight, 185–186, 185 (fig.), 189
 as optical illusion, 189–190
See also examples
- parent nodes, 111–112, 117–118, 129
- Pascal, Blaise, 4–5
- Pasteur, Louis, 228
- path analysis
 in economics, 86
 in social sciences, 85–86
 Wright, S., on, 86–89, 324
- path coefficients, 77, 223, 251
- path diagram
 for birth-weight example, 82–83, 82 (fig.)
 of Burks, 308–309

- of Wright, S., 74–77, 75 (fig.), 85–86, 221, 260–261
Paz, Azaria, 381
Pearl, Judea, ix, 24, 51, 328, 331
Pearson, Egon, 271–272
Pearson, Karl, 5, 62, 78, 85, 180, 222
causation and, 71–72
on data, 87–88
Galton and, 66–68
on skull size, 70 (fig.)
on spurious correlation, 69
as zealot, 67–68
philosophers, on causation, 47–51, 81
physics, 33–34, 67, 99
Pigou, Arthur Cecil, 198
Pinto, Rodrigo, 236
placebo effect, 300
polynomial time, 238
Porter, Ted, 67
potential outcomes, 155, 260
potential outcomes framework, 155
prediction, 278, 280
intervention and, 32
in science, 36
preponderance of evidence, 288
pretreatment variables, 160
Price, Richard, 97
prior knowledge, 90, 104
probabilistic causality, 47–51
Probabilistic Reasoning in Intelligent Systems (Pearl), 51
probability, 43–44, 46, 90, 110
Bayes on, 97–98, 102
Bayesian networks and, 358–359
in but-for causation, 287
causation and, 47–51
of guilt, 288
Ladder of Causation and, 47–49, 75
language of, 102–103
or necessity, 294
over time, 120–121, 121 (fig.)
raising, 49
of sufficiency, 294
See also conditional probability; inverse probability
probability table, 117 (table), 128–129
probability theory, 4–5
product
of coefficients, 327
indirect effect as, 328–329
Provine, William, 85
provisional causality, 150
proximate cause, 288–289
Pythagoras, 233
quantitative causal reasoning, 43
queries, 8, 10, 12 (fig.), 14–15
causal, 27, 183
counterfactual, 20, 28 (fig.), 36, 260–261, 284
in Ladder of Causation, 28 (fig.), 29, 32
mediation, 131
See also “Why?” question
randomized controlled trial (RCT), 18, 132–133, 143–147
in causal diagram, 140, 148–149, 149 (fig.)
confounders and, 149–150
in epidemiology, 172–173
Fisher on, 139–140, 143–144
as “gold standard,” 231
with noncompliance, causal
diagram for, 252–253, 253 (fig.)
observational studies versus, 150, 229
recombinant DNA, 369
reduction, of data, 85
regression, 29, 325
See also linear regression
regression coefficient, 222–223
regression line, 60–62, 61 (fig.), 221–222
regression to the mean, 57–58, 67
Reichenbach, Hans, 199, 234
Reid, Constance, 271–272
representation
acquisition and, 38
of information, in brain, 39
representation problem, 268

- reversion, 56–57
 Robins, Jamie, 168, 329–330, 329 (fig.), 333–334
 on confounding, 150
do-calculus and, 236–237, 241
 on exchangeability, 154–156
 robots, ix–x
 AI, 291
 causal inference by, 2, 350, 361, 361 (fig.)
 communicating, with humans, 366
 as moral, 370
 soccer, 365–366
 root node, 117
 Rubin, Donald, 269–270, 270 (photo), 275, 283
 causal model of, 261, 280–281
 on potential outcomes, 155
 Rumelhart, David, 110, 111 (fig.), 268
 Sackett, David, 197–198, 198 (table)
Sapiens (Harari), 25
 Savage, Jimmie, 316
 Savage, Leonard, 204–206
 scatter plot, 59 (fig.), 60, 62
 Scheines, Richard, 350
 Schuman, Leonard, 182
 science
 data in, 6, 84–85
 history of, 4–5
 mathematics and, 4–5, 84–85
 prediction in, 36
 See also causal inference; social sciences
 scientific method, 108, 302
 SCMs. See structural causal models
 Scott, Robert Falcon, 298 (photo), 302, 303 (fig.)
 Searle, John, 38, 363
 seatbelt usage, 161–162
 Sedol, Lee, 360
 Seeing vs. doing, 8–9, 27, 130, 149, 233
 self-awareness, 363, 367
 SEM. See structural equation model
 sensitivity analysis, 176
 sequential treatment, 241 (fig.)
 Shafer, Glen, 109
 Sharpe, Maria, 68
 Sherlock Holmes, 92 (photo), 93
 Shpitser, Ilya, 24, 238–239, 243, 245, 296–297
 Silicon Valley, 32
 Simon, Herbert, 79, 198
 Simpson, Edward, 153–154, 208–209
 Simpson's paradox. *See examples*
 smoking. *See examples*; surgeon general's advisory committee; tobacco industry
 smoking gene, 174–175, 224–227, 339–343, 341 (fig.), 342 (fig.)
 smoking-cancer debate, 166 (photo), 167–179
 Snow, John, 168, 245–249
 social sciences, 84–86
 social status, 307
 sophomore slump, 56–58
 Spirtes, Peter, 244
 Spohn, Wolfgang, 350
 spurious correlation, 69–72
 spurious effects, 138
 stable unit treatment value
 assumption (SUTVA), 280–281
 Stanford-Binet IQ test, 305–306
 statistical estimation, 12 (fig.), 15
 statistics, 5–6, 9
 anthropometric and, 58
 canned procedures in, 84–85
 causal inference in, 18
 causality and, 18, 66, 190
 confounders in, 138–139, 141–142
 methods of, 31, 180–181
 objectivity and, 89
 skepticism in, 178
 See also Bayesian statistics
 Stigler, Stephen, 63, 71, 147
 Stott, Peter, 292–294
 strong AI, 3, 11
 causal reasoning of, 20–21
 counterfactuals for, 269
 free will and, 358–370
 as humanlike intelligence, 30, 269
 Strotz, Robert, 244

- structural causal models (SCMs), 260–261, 276–280, 276 (fig.), 283–286
structural equation model (SEM), 86, 285
subjectivity
 Bayes on, 90, 104, 108
 causal, 90
 causal analysis and, 89
sufficiency, probability of, 294
sufficient cause, 288–291, 295
sum of products rule, 324
Supreme Court, U. S., 288, 316
sure-thing principle, 204–206, 316
surgeon general's advisory committee, 179–183, 180 (fig.)
surrogates, 152
SUTVA. *See* stable unit treatment value assumption
Szent-Gyorgyi, Albert, 304
- Teague, Claude, 177
temporal relationship, 181
Terman, Lewis, 305, 307
Terry, Luther, 179, 182
testability, 116, 242, 283, 381
testable implications, 12 (fig.), 13, 283
theology, 97
Thinking, Fast and Slow (Kahneman), 58
thinking machines, 10
Thomson, J. J., 53
threshold effect, mediation and, 325, 326 (fig.)
Thucydides, 262
Tian, Jin, 238, 243
- time-varying treatments, 241
tobacco industry, 170, 171 (fig.), 177–179
total effects, 300, 317
tourniquet. *See* examples
“Toward a Clearer Definition of Confounding” (Weinberg, C.), 162
transfer, of information, 194
transformations, in *do*-calculus, 233–234, 238
transparency, in *do*-calculus, 239–240
transportability, 353, 354 (fig.), 356
Treatise of Human Nature (Hume), 264–265, 265 (fig.)
Turing, Alan, 27, 29, 36–37, 108–109, 358
Tversky, Amos, 290
“Typical Laws of Heredity” (Galton), 54
- uncertainty, 4, 109, 143
United States Department of Agriculture (USDA), 73
universal mapping tool, 219–220
- VanderWeele, Tyler, 185, 342–343
Variables
 causally relevant, 48–49
 instrumental, 249–250, 249 (fig.), 257
 in intervention, 257
 pretreatment, 160
 in probability, 48–49
Verma, Thomas, 87, 242, 245
Virgil, 3
vos Savant, Marilyn, 190–193, 191 (table), 196
- Wainer, Howard, 216, 217 (fig.)
Wall, Melanie, 328, 331
weak AI, 362
weighted average, 106
Weinberg, Clarice, 162–163
Weinberg, Wilhelm, 65
Weissman, George, 177
Welling, David, 344
Wermuth, Nanny, 240–241, 241 (fig.)
Whig history, 65–66, 80
“Why?” question, 299–300, 349–350
Wilcox, Allen, 186–187
Winship, Christopher, 115, 350
Wold, Herman, 244
would-haves, 329–336
Wright, Philip, 72, 250–252, 251 (fig.)

- Wright, Sewall, 5–6, 18, 244, 309
on causation, 79–81
“Correlation and Causation” by,
82
on developmental factors, 74–76,
75 (fig.)
Fisher and, 85
guinea pigs of, 72–74, 74 (fig.), 222
on model-free approach, 88–89
Niles on, 78–81, 84
on path analysis, 86–89, 324
on path coefficients, 223, 251
path diagram of, 74–77, 75 (fig.),
85–86, 221, 260–261
Yerushalmy, Jacob, 167–169, 174,
183–184
Yule, George Udny, 68–72, 222
Zadeh, Lotfi, 109