Index

A-current, *see* current, A-current
adaptation
  in conductance model, *see* neurons, Wilson model neuron
  in LIF neuron, *see* leaky integrate-and-fire neuron
  regular spiking cell, 116
adaptive filtering, *see* control theory, Kalman filter
alphabets
  and coding, 6, *see also* neural codes
  neural activity as, 7
  physical properties as, 7, 29
AMPA receptors, 179, 246
analog-to-digital converter, 30
  representation in, 31
Aristotle, 275
arm movement, 52–56, *see also* vector, representation
artificial neural network, 158, 279
  hidden layer analysis, 158
attractor networks, 250–254, *see also* dynamic systems theory
  and noise reduction, 259
  computational properties of, 259

basic representation, *see* representation, basic
basis functions, 2, 17, *see also* functions, representation
  compared to basis vectors, 191
  Fourier basis, 191, 204
  Legendre basis, 201
  of possible transformations, 198
  orthonormal, 65
basis vectors, 185–191, *see also* vector, representation
  and neurobiological representation, 191
  biorthogonal, 191
  Cartesian, 186
  complete versus overcomplete, 190
  defined, 186
  non-orthogonal, 187
  orthogonal, 187
  overcomplete, 186
  spanning a space, 186
Bayes, 276, *see also* statistical inference
biorthogonal basis, *see* basis vectors
biphasic oscillators, *see also* lamprey, biphasic oscillator models of

cerebellum, 280
cognitive science, 219
coincidence detection, 155, *see also* transformations, nonlinear
communication channel, 143
  learning, 294
communication theory, *see also* information theory
communications theory, 1, 6, 8
computation, *see* transformations
connection weights
  analytically determining, 145
  and dynamics, 228, 235
  biasing functions, 161
  dynamically changing, 280
  for cross product, 175
  for nonlinear transformations, 158
  for population-temporal representation, 146
  for vector transformations, 152
  forcing positive, 166
  learning, *see* learning
  negative, 160–167
  standard problems with, 161
control theory, 2, 220
  adapted to neurobiology, 18
  and statistical inference, 287
  classical, 220
  internal description, 221
  Kalman filter, 287–293
    applied to vision, 291
    prediction-correction form, 289
    stability of, 291
    system diagram, 290
  matrices defined, 221
  modern, 220
  neural, 222–230
    basic level description, 225
    generic subsystem, 228
    higher-level description, 226
    Kalman filter, 289
    neural integrator, 233
    working memory, 245
  nonlinear, 18, 222, 240
  state equations, 221
  time invariant, 221
  time-varying, 240
correlation time, *see* leaky integrate-and-fire neuron
CPG, *see also* lamprey, and central pattern generators
current
  A-current, 119
  driving, 35
  neuron bias, 35
  potassium, 83, 116, 119, 124
  sodium, 83, 124
  soma, 35, *see also* neurons, biophysics of
curse of dimensionality, 279
cybernetics, 220

decoding, 6, *see also* representation
  and connection weights, 17
  linear binary, 32, 33
  linear temporal, 92–105
  nonlinear, 112
  nonlinear versus linear, 16
  optimal

observability of, 17
without noise, 37
population-temporal, 131
representational, 9, 13
temporal, 92, 103, *see also* temporal representation
plausibility, 113
transformational, 13, 158, 176, *see also* transformations
with basis vectors, 187, *see also* vectors, representation
with PSCs, 113, 115
with temporal filters, 98
Deiters' nucleus, 172
seealsovestibular system, 350
delta function
as neural spike, 82, 92
to define tuning curves, 68
dendrites, 10
and subunits, 160
nonlinear, 154, 156, 159
synaptic dynamics, 223, 230
design specification
description of, 21
example, 46, 54, 74, 174, 264
dot product, 51n, 186
dynamic systems theory, 250, *see also* attractor networks
and control theory, 258
and recurrent networks, 252
and single neurons, 120, 124
and subnetworks, 258
chaotic attractor, 259
cyclic attractor, 267
line attractor, 252, *see also* neural integrator
plane attractor, 254
point attractor, 237, 251
ring attractor, 253, 257
dynamics, *see also* control theory
higher-level, 15
importance of, 219

Einstein, 168
encoding, 6, *see also* representation
and connection weights, 17
binary, 31, 32
temporal, 92
with basis vectors, 187
eye position, *see also* neural integrator
drift, 232
horizontal, 36, 44–49, 136–139, 232–243

Fourier basis, *see* basis functions
Fourier decomposition, 65, *see also* basis functions
function
decoding, 69
optimal linear, 68
design specification for, 75
encoding, 66
probability density function representation, 278
representation, 63–69
defining, 65
distinguishing from vector, 72
encoding function, 66
examples, 72
in LIP, 74
multi-modal, 79
population-temporal, 138
probability density functions, 278
relation to vectors, 69–72, 245
summary, 80
transformations, 200
functions
decoding, *see also* transformations
defining sets of, 64
sets of
coefficients, 70
estimating coefficients, 71
for temporal coding, 99
Monte Carlo estimates, 71

Γ, 38
decomposition of, 192–196
with noise, 43
ganglion
retinal, 7

head-direction system, 253
heterogeneity, 210–216
and dynamics, 257
and experiments, 12
and representational capacity, 213
and representational usefulness, 215
and supported transformations, 216
importance of, 210, 216
higher-level representation, *see* representation, higher-level
hippocampus, 253

implementation
description of, 21
example, 47, 55, 58, 77, 136, 175, 233, 244, 265
information capacity, *see* neurons, information capacity of
information theory, 2, 110, *see also* neurons, information capacity of
interneurons, 161

jitter, *see also* noise

and correlation times, 108
and temporal code, 133
in neural transmission, 41

Kalman filter, *see* control theory, Kalman filter
Kirchoff, 85

labyrinths, 169, *see also* vestibular system
lamprey, 260–273
and central pattern generators, 260
and control theory, 261, 265, 272
and traveling waves, 262
as a cyclic attractor, 267
biphasic oscillator models of, 260, 261
connectivity, 271
dynamic tensions in, 265
fluid dynamics and, 263
integrating top-down and bottom-up data, 260
locomotion, 260
mechanics of, 265
neurophysiology and behavior of, 261
simulating at multiple levels, 270
top-down and bottom-up data, 271
Laplace transform, 223
large-scale models
lamprey, 260
vestibular system, 168
working memory, 244
lateral intraparietal cortex, 64, 72, 244, *see also* working memory
anatomy and physiology of, 73
function of, 73
neuron tuning curves in, 74
leaky integrate-and-fire neuron, 81–89
and correlation times, 109
as an RC circuit, 84
decoding spikes from, 107
derivation of, 83
effects of parameter changes, 87
implausibility, 88
information transmission in, 105–115
optimal temporal decoders, 105
plausibility, 82, 88
power in spike train, 108
rate equation derivation, 86
rate model, 36
voltage equation, 85
voltage trace, 82
with adaptation, 116
decoding, 119
information capacity, 118
learning, 293–300
analyzing weights from, 295
as fine tuning, 294
challenges posed by, 298
compared to analysis, 297
Hebbian, 294, 295
limitations, 14
the communication channel, 294
versus analysis, 14
Legendre basis, *see* basis functions
LIF neuron, *see* leaky integrate-and-fire neuron
linear systems theory, 219, *see also* control theory
look-up table, 279

MatLab simulation package, xvii, 12n, 19
mean square error
and SVD, 195
and transformational decoders, 158
decreases as $1/N$, 47, 190
due to noise, 43
for temporal decoding, 100
matrix-vector notation, 192
minimizing, 38
residual, 209
static, 43
decreases as $1/N^2$, 48
with noise, 42
without noise, 37
modern control theory, *see* control theory
modularization, 151, 173
motor cortex, *see* arm movement
MSE, *see* mean square error
multiple level simulations, *see* lamprey

negative weights, *see* connection weights, negative
neural codes, *see also* representation
not choosing between, 91
population, 11–13
rate, 7, 89, 108
synchrony, 7
timing, 7, 90, 108
neural control theory, *see* control theory, neural
neural engineering
addendum to principles of, 16, 18
defined, 1–3
first principle of, 15, 16, 39, 230
methodology, 15, 19–23
summary of, 22
principles of, 15–19, 230–231
second principle of, 15, 17, 231
third principle of, 15, 18, 231
neural integrator, 36, 44, 136, 232–243, *see also* eye position
and cellular properties, 241
and network properties, 240
as a line attractor, 253
block diagram, 233

controlling dynamics of, 239
drift velocity of, 237
dynamics of, 238
effective time constant of, 235
goldfish, 19, 243
human, 243
input/output transfer function, 49
neurobiological systems
as representing, 4–13
theory of, 23–25
neurons
adaptation, *see* adaptation
affinity for performing statistical inference, 279
and inhibition, 161
and noise, *see* noise
and transistors, 11, 30, 33, 39, 40
as devices, 9–11, 41
biophysics of, 10, 34
canonical models, 115, 122
cell membrane, 83
classes of, 119, 124
conductance model, 123
diversity, 1, 2
heterogeneity of, *see* heterogeneity
Hodgkin-Huxley, 123
identifying tuning curve of, 66
information capacity of, 10, 19, 40, 109–115
adapting LIF model, 118
conductance model, 125
LIF neuron, 112
LIF neuron with PSCs, 113, 115
model summary, 127
neurobiological examples, 110
per frequency channel, 111
θ-neuron model, 122
inhibition, 166
memory in, 10
pairs, 94–96, 242
and linearity, 95
examples, 94
persistent activity in, 252, *see also* working memory
populations of, 11, *see also* population representation
power consumption, 41
precision of, 10, *see also* neurons, information capacity of
Purkinje cells, 280
regular spiking, 116
reliability, 41
response function defined, 34
θ-neuron model, 118
tuning curve defined, 34
various models of, 115–126
Wilson neuron model, 123
neuroscience
and dynamics, 219
and representation, 5
central problem of, 5
explanations in, 5
interplay of experiment and theory, 180
theoretical, xiii
theory for, 24
Newton, 24, 29, 262
NMDA receptors, 179, 246
noise, 18, 40–44, 47, 55, 132, 208–210, 275, 284, 313
nonlinear control, *see* control theory, nonlinear
nuclei prepositus hypoglossi, 36, 44, 232, *see also* neural integrator
neuron tuning curve, 36
population tuning, 38

opponency in neurons, *see* neurons, pairs
orthogonal basis, *see* basis vectors
otolith, 168, 169, *see also* vestibular system
overcomplete basis, *see* basis vectors

pairs of neurons, *see* neurons, pairs
pattern theory, 276, *see also* statistical inference
PCA, *see* principle components analysis
PDF, *see* statistical inference, probability density function
population representation, 12, 33–44
function, *see* function
relation to temporal representation, 131
scalar, *see* scalar
vector, *see* vector
population-temporal filter, 131
population-temporal representation, 11, 129–132
and noise, 132–136
and PSCs, 132, 137
decoding, 140
encoding, 139
finding optimal filters, 132
Monte Carlo estimates, 132
of functions, 138
postsynaptic current, *see* temporal representation
potassium current, *see* current, potassium
primary visual cortex, 291
orientation tuning, 66
tuning curve, 67
principle components analysis, 192, 201
probability density function, *see* statistical inference, probability density function
probability theory, 275, *see also* statistical inference
PSC, *see* postsynaptic current
pseudo-inverse, 209
push-pull amplifiers, 94

refractory period
absolute, 83–85, 88, 105
relative, 121
representation
analysis, 185, 206–210
and codes, 6
analogy, 9
differences, 8
and explanation, 4, 5
and noise, 209, *see also* noise
and use, 6, 180, 182
basic, 48, 62, 225
capacity, 207, 213
discovering, 8, 180
distributed, 33
engineered, 30–33
goodness of, 206
and dynamics, 236, 237
and heterogeneity, 210
higher-level, 48, 62, 225
importance of, 29
improves as $1/N$, 47–48
in digital computers, 30
in neuroscience, 6
mixing levels of, 234
Morse code, 6
neurobiological, 4, 33, *see also* population-temporal representation
matrix-vector notation, 192
with noise, 42
overcomplete, 190, 269, *see also* basis vectors
population, *see* population representation
population-temporal, *see also* population-temporal representation
precision of, 44, *see also* noise
quantifying usefulness, 208, 215
relation, 5, 181, 189
seeming arbitrariness of, 8, 180
temporal, 81, *see also* temporal representation
utility of, 4
representational hierarchy, 13, 61–63
definition of levels, 80
multiple levels, 269
table of, 63
usefulness of, 62
rostral medial vestibular nucleus, 36, 45, *see also* vestibular system

saccular macula, 169
saddle-node bifurcation, 120, *see also* dynamic systems theory
sampling densities, 2
scalar
encoding magnitude, 30
magnitude and unit, 29
neuron tuning curve, 36
representation, 29, 42–44
summary, 80
semicircular canals, 57, 168, 169, *see also* vestibular system
biophysics of, 57
shifter circuit, 280
singular value decomposition, 78, 194
singular values, 194
and importance, 197
and noise, 209
and vector transformations, 204
cutoff value, 209
Gaussian versus linear populations, 205
sodium current, *see* current, sodium
span, *see* basis vectors
stationarity, 99
statistical inference, 275–281
and dynamics, 284
and neural architectures, 279
and the Kalman filter, 287–293
bottom-up evidence, 280
conditional distribution, 277
disambiguating evidence, 281, 283
feed-forward, 278
feedback architectures, 280
joint distribution, 276
marginal, 277
multi-modal distributions, 277
non-stationary, 286
parameter estimation, 283–287
probability density function, 277
top-down evidence, 280
SVD, *see* singular value decomposition
system description
description of, 19
example, 44, 53, 57, 73, 169

temporal representation, 89–105
and correlation times, 102, 107
and encoding functions, 104
and neuron pairs, 96, 100
and noise, 133
and optimal filters, 102
and windowing data, 101
as linear filtering, 104
combining rate and timing codes, 91
debate concerning, 89
decoding, 97, 103
plausibility, 113
with PSCs, 113, 115
defining signal ensembles, 99
encoding, 92

encoding and decoding process, 93
optimal filter, 106
optimal filter compared to PSC, 106
relation to population representation, 131
residual error, 102
top-down and bottom-up data
integrating, *see* lamprey
transformations, 13–15
addition, 148
analysis, 185, 196–205
and noise, 200
and dynamics, 14
and modularization, 150
and representation, 13
and SVD, 196
basis of
ordering, 197
in communication channel, 143
in neurobiology, 143
linear, 143–152
nonlinear, 153–160
as cellular property, 155, 156
as network property, 157
cross product, 173
examples, 153
in neurobiology, 17
orthogonal basis of, 198
polynomial, 201
supported by Gaussian tuning curves, 204
supported by linear tuning curves, 200
utility of, 4
vector
analysis, 202
linear, 151
translational vestibular ocular reflex, 177

utricular macula, 169

vector
decoding, 52
optimal linear, 53
optimal versus non-optimal, 56
preferred direction, 53
defined, 185
encoding, 51
neuron tuning curve, 52
cosine, 52, 53
preferred direction, 51
relation to functions, 69–72
representation, 49–56, *see also* basis vectors
equivalent, 62
examples, 49
orthogonal versus overcomplete, 59
summary, 80
with LIF neurons, 51
representation in vestibular system, 169
space defined, 186
vesicle unreliability, 41
vestibular system, 57–59, 168–182

working memory, 72–79, 244–249, *see also* lateral intraparietal cortex
and activity bumps, 249
and decoded bumps, 248
increase in firing rate during, 250
multiple targets, 72, 244, 248
parametric, 73, 244, 248