

— Handbook of Fourier Analysis & Its Applications

Robert J. Marks II

OXFORD
UNIVERSITY PRESS

2008

Index

A

- a.k.a., **ix**, 155, 362, 411, 503, 570
- Abbott, Edwin A., 326, 680
- Abel transform, 226, **345–348**, 401–402, 406–407
- Abel, Niels Henrik, 519
- absolute
 - convergence, vi, 24
 - error, 366
 - value, 73
- absolutely convergent, **61–62**, 72–73, 266
- additive, 9
 - basis, 598
 - closure, 590, 605–607
 - correlation, 462
 - noise, 18, **288**, 292–294, 302, 323, 325, 456, 459, 461–463, 518, 682, 699
 - sample noise, 265
 - systems, 9, **105–106**, 108, 110–113, 135, 142, 630
- acoustics, 3–4, 495, 610, 612, 624, 692, 706, 728, 735
- acronym table – see tables
- additively, 630
- additively idempotent time scale, ix, **595**, 603.
Also see AITS
- Airy
 - disc, 637–638
 - pattern, 637, 657
 - George Biddell, 518
- AITS, ix, **595–598**, 601–608. Also see –
additively idempotent time scale
AITS hull, **596–597**
- algebraic decay, 591, 596
- aliasing, 4, 9, 55, **222**, 236–237, 253–254, 283, 288, 309, 374, 376, 382, 390, 396–397, **451–472**, 483, 489, 684, 686, 691, 692, 697–698, 581, 705, 707, 715, 718–719, 722, 730, 732, 734–735
- almost sure convergence, 177
- alternating projections onto convex sets, vii, x, 433–435, **495**, 551–553, 716, 721.
Also see – POCS
- AM, ix, 68, 122, 133. Also see – amplitude modulation
- ambient temperature, 106
- ambiguity function, 441, 445, 681, 715, 728–729, 735
- amortization, 8, **656**
- amplitude modulation, ix, 6, 68, **122–123**, 133–134, 204, 276. Also see – AM
- analytic signals, xiv, 12, 64, 77, 134
- angular
 - displacement, 399
 - Fourier transform, 126, 680
 - frequency, 625
 - intervals, 547
 - spectrum, **626–630**, 657
 - variable, 399
- annulus, 342, 572, 574, 607
- antenna, 122, 624, 643–644, 684, 686, 691, 703, 714, 726, 729, 736, 741
- anti-derivative, 587
- antiextensive, **581**, 583, 595, 608
- aperiodic, 354, 358, 704
- aperture, 4, 415, 532–533, 544, 624, 634–637, 642–644, 657, 659, 687, 698–699
- apodization, 415, **644**, 731
- Arabshahi, Payman, vii
- arbitrary
 - but fixed, 586, 596
 - closed subset, 604
 - complex weights – see complex weight
 - constant, 645
 - frequency, 424, 657, 734
 - function, 248, 429
 - integration, 15
 - interval, 564
 - number, 385
 - period, 14
 - point, 501
 - phase, 416
 - rational time, 424
 - signal, 484
 - tile shape, 373
 - time scale, 605

- arbitrary (*cont'd*)
 variation, 220
 vector, 506–507, 510, 514, 522
- arctan, 22, 91, 228–229, 292, 312–313, 460
- arithmetic mean, 14, 439
- array
 aperture, 643–644
 beam – see beam array
 detector, 250
 function, xii, 23, **32–35**, 65–66, 69, 90, 99, 100, 103, 154, 169, 266, 267, 272, 276, 454–455, 466, 468, 470, 489, 643, 663
 imaging, 3, 732
 linear – see linear array
 of circles, 378
 of Dirac deltas, 373
 of squares, 392
 pattern, 643–644
 phased – see phased array
 pixel – see pixel array
- associative, 115–116, 576
 memory, 7, **516–521**, 525–527, 529, 550, 691, 716, 730
- astrophysicists, 411
- asymptotic Gaussian, 189
- asymptotic graininess, **597–601**
- Atlas, Les E., viii, 436, 551–553, 691, 716, 721, 725, 744
- atmospheric gases, 6
- audio, 3–4, 68, 122, 234, 439, 613, 695, 743
- Augustine, Saint, 411, 681
- autoconvolution, 133, 186, 203, 419
- autocorrelation, xi, xiii, 15, 194–200, 204, 214, 233, 289–292, 309–312, 316–317, 323, 384, 427, 457, 460–464, 486, 700, 708
- average, 124, 160, 176–179, 182, 186, 196, 204, 215–216, 277, 303–304, 306, 439, 517, 519, 533, 676, 682, 698, 737. Also see – sample mean
 image, 179, 517, 519, 533
 power, 124, 196, 204, 215–216, 737
 interpolation noise, 303–394, 306
 sampling density, 277, 698
- function, 39, 49, 101, 220, **224–225**, 231, 235, 682, 685, 689, 694, 699, 701, 706, 709–710, 712, 719–720, 725, 726, 732–734, 737, 743. Also see – bandlimited signals
 signal, ix, xii, xiv, 8–9, **12**, 68, 71, 150, 217–219, 226, 231–232, 234–235, 239–240, 242–244, 250–251, 261, 263, 265, 275–277, 288, 307, 316, 320, 323–324, 376, 382, 394, 397, 447–449, 474, 477, 480, 483, 485–487, 495, **507**, 514–517, 535, 537, 550, 685–690, 692, 697, 702–703, 709, 711–712, 714–717, 720, 723, 725, 727–728, 734, 736, 740–742. Also see – bandlimited function
- bandpass, ix, **121–123**, 134–135, 267–268, 270–272, 278, 301–302, 369–371, 413, 418, 439, 683, 686, 709, 734, 738
 filter, 121, 123, 134–135, 369, 413, 439, 683
 function, **267–268**, 270, **301–302**
 sampling, **270**, 302, 686, 709, 734, 738
 signal, 268, 270–271, 418, 686
- bandstop filter, **121**, 135, 369–370
- bandwidth, xii, xiv, 12, 49, 68, 120, 122, 139, 218–219, 221–222, 227, 231–232, 235–236, 239–241, 243, 247–248, 252, 261, 264, 267, 271, 272, 274–276, 276, 280, 289, 293–294, 304, 314, 397–398, 429, 429, 450, 455, 465–467, 470, 473, 475, 477, 482–483, 485–486, 507, 514–515, 535, 537, 685, 699, 702, 705, 713, 716–717, 731, 737, 742
 equivalence, **397**
 interval, 232
- Bartlett window, 415, 419
- baseband, 68, 122–123, 133–134, 204, 268–269, 277
 signal, 122–123, 133–134, 204, 268, 277
- bastinadoed, 413
- Bayes, Rev. Thomas, 519
- BE, ix. Also see bounded energy signals
- beam
 array, 547
 constraint, 555
 cross section, 545–546
 design, 545–546
 dose, 547
 element, 547, 554–558, 560–561
 intensity, 546, 558–559, 562
 splitter, 643
 intensity, 546
 position, 554
 profile, 545–546, 558–559, 561–562
 projection, 546
 steering, **644**
 synthesis, 8
 vector, 547, 556
- B**
- Baby Senator image, 182
- back projection, 352
- bandlimited, ix, xii, xiv, 8–9, **12**, 39, 49, 61, 68, 71–72, 101–102, 133, 139, 150, 217–222, 224–227, 230–237, 239–244, 250–251, 261–263, 265–266, 271, 273, 275–278, 288, 307, 309, 314, 316, 320, 323–325, 376, 382, 394–395, 397–398, 447–450, 465, 472, 474–475, 477, 479–480, 482–488, 491, 493, 495, 507, 514–517, 535, 537, 550, 682, 685–690, 692, 694, 697–699, 701–703, 706, 708–712, 714–720, 723–737, 740–743

- weights, 445
 - width, 643–644
 - beamforming, 8, 126, 415, 495, 624, 643, 697, 713, 742
 - beat frequency, 429, 435
 - bel, 413
 - bell shaped curve, 159
 - Benedictine abbey of Saint Benoît-sur-Loire, 5
 - Bernoulli
 - random variable, **169**
 - trial, **169–170**
 - Daniel, 518
 - Jacob (Jacques), 518
 - Nicolaus (II), 518
 - Bertrand's paradox, 565
 - Bessel
 - functions, xii, xvi, 9, **37**, 39–41, 43, 64, 69, 89, 92–93, 95–96, 133, 141, 202, 263, 342–345, 401, 406, 415
 - Friedrich Wilhelm, 326, 518
 - beta
 - function, xii, 36–37, 164
 - probability function, 153, 165, 202
 - random variable, 153, 163–165, 202, 209, 210
 - bias, 122, 124–125, 134, 204, 216, 276, 313–316, 318–319
 - biased estimate, 313
 - BIBO, ix, 107, 110–112, 142. Also see – bounded input-bounded output stability
 - bilateral
 - cosine transform, **65**, 83
 - Laplace transform, **64**
 - binary
 - image, 182, 570, 575–578, 580, 582, 584
 - string, 365
 - binomial
 - coefficients, xiii, 36, **662**
 - random variable, **170–172**, 175, 190, 194, 202–203
 - series, 170, 203, 481, **662**
 - bioengineering, 424, 434
 - bioinformatics, 495
 - biomedical
 - engineering, 3, 724
 - signal, 424, 434, 684
 - bipolar, 517
 - bit packet, 160
 - bits, 364
 - BL, ix. Also see bandlimited signals
 - Black, H.S., 218, 684
 - Blackman window, 415, 420, 422, 685
 - block orthogonal, 414
 - blurred
 - face, 517
 - image, **147**, 696, 705, 722, 741
 - motion – see motion blurr
 - Bohner, M., 586, 680, 685
 - Bohr, Niels Henrik David, 151, 685
 - Boltzmann's constant, xii, 198, 407
 - Borel, Emile, 218–219, 685
 - Born-Jordon kernel, 411, 543
 - Bortfeld, Thomas, 448, 685, 735
 - Bortfeld's geometry, 560–561
 - boundary. Also see Fresnel – Fraunhofer
 - boundary & inside boundary & outside boundary
 - conditions, 127–128, 130, 164, 228, 612, 618, 656
 - for the spectrogram, 440
 - of a closed convex set, 497
 - of a region, 380
 - of the Minkowski addition, 571
 - wide sense stationary stochastic process, 204
 - value problems, 7, 610, 692, 700, 703, 707, 743
 - bounded. Also see – error bound & lower bound & measurable
 - bounded signals & unbounded & upper bound
 - bandlimited function, 102, 682
 - derivative, 512
 - energy signals, ix, 305, **511**
 - first difference, 512
 - input-bounded output stability, ix, **107**, 110, 142. Also see – BIBO
 - inverse Fourier transform, 101
 - noise level, 482
 - signal, ix, **11–12**, 67, 71, 107, 495, **512**, 527, 688
 - bow tie
 - constraint, 428, 539, 543–544
 - untruncated, 544
 - boxcar window, 415, 419–420, 423–424
 - BPF – see band pass filter
 - Bracewell, Ronald N., vi, 686
 - Bradley, Walter L., viii
 - Brahme's butterfly tumor, 557, 559, 686
 - Bravais lattice, 327
 - Bregman, L.M., 495, 686
 - broadband signal, 122, 700, 725
 - Brother Ray image, 179, 185
 - BS, ix. Also see bounded signals
 - bugle, 613, 616, 618
 - bunched samples, 252, 257. Also see – interlaced samples
 - byte, 364, 366, 517, 532
- ## C
- CA, ix. Also see constant area signals
 - Cantor, Georg Ferdinand Ludwig Philipp, 139, 689, 694
 - capacitors, 106, 116
 - cardinal series, **49**, 150, 217–220, 222–225, 227, 229, 231–235, 241–243, 245–249, 261, 265–266, 272–274, 277–278, 284–285, 288–290, 294–295, 302, 313–314, 320–321, 323, 449, 461, 484,

- cardinal series (*cont'd*) 682, 684, 686, 688–689, 697, 704, 709–710, 718, 722, 729, 733–734, 739
- carrier, *x*, 68, 122–124, 133–134, 276
frequency, 68, 122, 276
carrier frequency phase, 124
- Cartesian
coordinates, 15
Cartesian product, *xi*, 591–593
- CAT, *ix*, 327
- cathode ray tube – see CRT
- Cauchy
autocorrelation, 323
A.L., 218, 687–688, 690, 738
– Bunyakovski – Schwarz inequality, **660**
characteristic function, 168
inequality, **660**
principle value, 167
probability density function, 166–167, 679
random variable, 153, 166–169, 175–176, 187, 209, 678–679
– Schwarz inequality, **660**
- causal
comb, 31–32, 78
convolution, 137
filter, 107, 440, 482
impulse response, 366
signal, 8, **12**, 15, 18, 46, 51, 64–65, 107, 111, 137, 140, 420, 482, 486–487, 495, 684, 705
sine wave, 420
system, **107–111**, 113–114, 135–136, 142, 144. Also see – nonanticipatory system
time scale, 586, 599
window, 420, 423
- causality, 6, 107, 111
- CD, *ix*, 4, 107
- cellular radio, 495, 726
- center of mass, 155, 174
- central
limit theorem, 6, 8, 160, **178–170**, 187–192, 202–203, 211, 676
slice theorem, **348–350**, 401, 406
tendency, 155
- cents, 610, **614–616**, 621–623, 656–657, 658–659
- chain rule, 347, 569
- characteristic functions, *xiii*, *xvii*, 6, **152–156**, 158–164, 166, 168–171, 174–177, 186–187, 201–203, 205–206, 210–211, 315, 318, 670
- Chebyshev's inequality, **157–158**, 178
- Chebyshev
filters, 107
polynomials, *xiv*, **42–43**, 50, 69, 89, 96–97, 167, 372
polynomials of the second kind, 9, **69**
Pafnuty Lvovich, 519, 610
- chemistry, 3, 716
- Cheung, Kwan Fai, *viii*, 516, 691, 726, 740
- chi random variable, **667–668**
- chi-squared random variable, 153, **162–164**, 175, 190, 201, 206, 664, 667–668, 673
- chirp, 432–434, 439, 544, 551–552
Fourier transform, **439**
- Cho, Paul S., *viii*, 554, 557, 559–562, 692, 711–712, 742
- Choi, Jai J., *viii*
- Choi-Williams distribution, 431
- chords, 412, 613, 616–621
- Christ, *v*
- chromatic
scale, 8
step, 411, 613–615, 621–622
- chromatography, 4, 739
- Churchill, Sir Winston Spencer, 495
- circularly symmetric, 341–346, 401, 406
- circular
aperture, 637
convolution, 51, **53–54**, 118–119, 466
convolution mechanics, **118–119**
harmonic, 344–345, 401
circular pupil, 377, 379, 385
radius, 395
spectrum, 387
support, 377, 379, 391, 394–395
- city block metric, 327
- clarinets, 613
- closed
convex sets, **496–497**
under addition, 590, 596, 608
under independent summation, **174–175**, 189
under Minkowski addition, 590, 596
- closing *xi*, **575**, 581, 583, 608
duality, **581**
- closure, 497, 590, 596, 605, 606–607
- cochlea, 4
- Cohen's GTFR, 7, 417, 431, 434, 438, 537, 689, 691, 696, 702, 710, 712, 713, 720, 722, 738–739, 741, 744
- Cohen, Leon, 424, 427, 692, 696
- coherent
demodulation, 122–125, 133–134, 268
demodulator, 122, 124
field, 629–630, 638, 695, 700
illumination, 377, 625, 684, 701
light, 4, 8, 377, 623, 630, 683, 735
optics, 628, 716
processor, 445, 702, 713, 715, 738
sonar, 4
wave, 626, 657
- Colerage, Samuel Taylor, *vii*
- colored noise, 323, 458
- column space, 506–507
- comb function, *xii*, 14, 23, 31–32, 34–35, 47, 51, 70–71, 78, 84, 100, 221–222, 235, 243, 253, 270, 273, 356–357, 373, 390, 392, 395–396, 466, 720
causal – see causal comb

- multidimensional – see multidimensional comb lemma
- communications engineering, 3, 685
- commutative, 115–116, 120, 576
- compact
 - disk, ix
 - support, 150
- complement, xii, 369, 506, 574, 578–579
- complete, 5, 47–48, 112, 139, 219, 224–225, 234, 238, 245, 267, 273–274, 278, 283, 315, 245, 326, 357, 403, 474, 475, 477, 482, 516, 528, 586, 661, 682, 704, 726
 - basis set, **48**, 273–274, 278, 474, 477, 704
- complex, 326, 545, 682, 685, 686, 693, 704, 710, 723, 737–738
 - arguments, 35–36
 - bandlimited signal, 235
 - computational – see computational complexity
 - conjugate – see conjugate exponential, 115–116, 419
 - even function, 82
 - field amplitude, 629
 - Fourier transform, 15, 82
 - frequency response, 116
 - function, 62, 190, 564, 660
 - image, 566
 - number, 12
 - odd function, 82
 - phase – see phase of a complex exponential
 - plane wave, 629
 - sinusoid, 31, 62, 412
 - signal, 239, 495
 - target, 558
 - Walsh function – see Walsh function
 - weights 628, 644
- compound interest, 647, 651–652, 655–656
- compounding, 647–649, 651–653, 656, 658
- computational complexity, 213
- computed axial tomography – see CAT
- condition, 8, 17, 24, 60, 67, 69, 95–96, 105, 127–128, 130, 136, 153, 164, 179, 186, 195, 224, 228, 248–249, 277, 298–299, 301, 383, 430, 470–472, 485–486, 612, 617–618, 642, 648, 655–656, 663–664, 691, 696, 711
 - number, 301, 470–472, 485, **663–664**
- cone, 428, 431, 434–438, 441, 444, 504–505, 508, 516, 527, 537, 539, 541, 543–544, 551–552, 693–694, 696, 709, 721, 725, 738, 744
 - constraint, 428, 541, 543–544, 551–552
 - kernel, 428, 431, **434–438**, 441, 444, 537, 693–694, 696, 709, 721, 725, 738, 744
- confluent hypergeometric function, xii, **202**, 209, 673
- conformal radiotherapy, 7–8, 495, **545–546**, 554, 557, 449–562, 685, 712
- conjugate, 15, 22, 45, 51, 70, 120, 127, 235, 269, 430, 438, 444, 472, 483, 489, 564, 629, 657, 735, 744
 - plane waves, **657**
 - symmetry, 45, 70, 120, 200, 235, 430, 472, 483, 489, 564, 629. Also see – Hermitian
- conservation of contours, 368
- constant
 - area signal, ix, **508–511**, 533, 545, 549
 - graininess, 597
 - phase signal, ix, **511–512**, 566, 628
 - Q , 415, 439, 695, 737
 - addressable memory, 516
- continuously sampled signals, 7, 9, **448–450**, 455, 461–463, 477, 480, 483, 715
- continuous, 11, 20, 36, 50, 80–81, 115, 120, 203, 224, 398, 449, 468, 564, 511, 586, 546, 608, 685, 689, 711, 716, 722, 732, 742. Also see – continuous time
 - circular convolution, 118
 - compounding, **649, 651–653**
 - domain, 328
 - dose, 549
 - functions, 9, 166, 173, 220, 327, 473, 509, 688, 732, 741. Also see continuous signal & continuous time signal & discontinuous function
 - image, 328
 - interest, 652
 - multidimensional, 330
 - noise, 324. Also see continuous white noise
 - position, 9
 - random variable, 153, 173
 - sample restoration, 462–464
 - sampling, vii, 10, 288, **447–448**, 463, 450, 463, 465, 467, 477, 483
 - short time Fourier transform, 441
 - signal, 104, 219, 508, 511, 564, 681–682, 690, 692, 704. Also see continuous function & continuous time signal
 - space, 326
 - stochastic process, xiii, 197. Also see – continuous time stochastic process
 - sum, 112
 - unit step, xiii
 - white noise, 9, **197–198**, 324, 457
- continuous time, 120, 196, 200, 425, 501, 718, 731. Also see – continuous
 - cone kernel, 441
 - convolution, 115, 141
 - filter, 135
 - Fourier transform, ix, 8, **13–15**, 18, 20, **45**, 50, 54, 81, 583, 587. Also see – CTFT
 - GTFR, 417, 427, 434
 - impulse response, xii, 121
 - periodic function, 67
 - rectangle, xiii
 - scale, 587, 604

- continuous time (*cont'd*)
 signal, ix, xiii–xiv, 6, **11–12**, 14, 50, 71, 193, 417–418, 570, 584, 586, 692, 704, 728–719. Also see continuous function & time signal
 solution, **653**
 stochastic process, 194. Also see – continuous stochastic process
 systems, **112**, 120, 139
 window, 415
- contractive
 function, 567, 569
 operators, 208, **558–559**, 562, 569
 iteration, 563, 567, 569
- control theory, 3
- convergence factor, 26, 32, 66, 83, 87
- convex
 cones, 496, **504–505**, 527
 cone hull, **504–505**, 527
 hull, **504–505**, 527
 set, vii, x, 7, 433–435, 438, **495–508**, 510–514, 517, 527–528, 533, 535, 537, 539, 542–543, 545–546, 548, 551–554, 557, 559–564, 567, 608, 686, 691–694, 702–703, 710, 712, 716, 721, 724, 726, 730–731, 735, 738–739
 slab, 508, 567
- convolution, vi, xi, xiv, 7, 15, 39, 32, 46, 51, 53–54, 107, **110–112**, 115, 117–119, 126, 130, 132–134, 137, 139, 174, 186–188, 198, 222, 226, 231, 236, 250–251, 263, 331–334, 346–347, 373, 413, 419, 443, 450, 456, 458, 466–467, 469, 570, 572–573, 583, 591, 592–595, 601–603, 631, 634–635, 680, 714, 716–719, 724, 725, 727, 732, 734. Also see – deconvolution
 algebra, **115–116**
 integral, 111, **115**, 117–118, 137, 333, 346, 401, 583, 631, 635, 732
 kernel, 456, 725
 mechanics, **117, 333–334**
 on a time scale, 592, 594, 601–602
 sum, **115**
 support, **572–573**
 tables – see tables
 theorem, **19**, 32, 333, 347, 413
- correlation, 51, 194, 198, 204, 226, 292, 324, 384, 457–458, 684, 693, 698, 703, 710, 714, 727. Also see – autocorrelation
 integral, 15
 length, 324
 theorem, 458
- cos, xii, 21–25, 27, 32, 37, 39, 42, 56–58, 65, 67–69, 77–78, 81–84, 87, 90, 92–94, 96–99, 110, 116, 121–124, 132, 198, 204, 214, 228–229, 232, 239, 262–263, 268–271, 276–278, 280, 283–284, 286, 291–292, 302, 306, 310–311, 324, 335, 337, 339, 341–342, 344, 350–352, 362, 367–369, 371, 402, 404, 420–423, 431, 438–439, 442, 445–446, 460, 488, 511, 567, 569, 588–594, 611–612, 627, 629, 670. Also see – cosine
 cosech, 23, 25–26, 86, 132, 140. Also see – hyperbolic cosecant
 cosh, **24**, 26, 163, 203, 211–212, 291–292, 311, 324. Also see – hyperbolic cosine
 cosine ix, xiv, 4, 6, 24, 56, 61–62, 65, 83, 117, 262, 284, 327, 360, 371, 420–424, 446, 627–628, 630, 657, 683, 717, 726–727. Also see – cos
 filter, 421, 423
 series, 422–424
 transform, ix, xiv, 4, 6, **56**, 65, 83, 327, 360, 717, 727
- cosinusoid, 123, 268
- cotan, 23, 31, 78, 87. Also see – cotangent
- cotangent, 23, 32, 78, 87, 304. Also see – cotan
- cotanh, 26
- countably infinite, 14, 230
- CP, ix. Also see constant phase signal
- Cramer's rule, 257, 275, 286
- cross-correlation, 194, 198, 204, 384
- CRT, ix, 395
- crystallography, 3, 700, 732, 740
- CTFT, ix, **13–16**, 20, 60, 587. Also see – continuous time Fourier transforms
 convergence, 189
 distribution function, xii, **151–152**, 187, 201–202
 spotting, 194
 sum, 51
- current, 11, 84, 116, 196
- cyclostationary stochastic processes, 323

D

- data noise level, 292, 384–386, 402
- daVinci, Leonardo, 518
- Davis, John M., viii, 583, 694, 702, 716
- dB, ix, 12, 68, 118, 366, 386–387, 413, 429, 544. Also see – decibel
- DCT, ix, 4, 7, 56–57, 72, 360, 362–366, 527, 680, 723, 735, 742, 744. Also see – discrete cosine transform
 basis functions, **362**
- de Broglie wavelength, 646
- decade, 53, 414, 737
- decibel, ix, 413. Also see – dB
- decimation, 387, 392–395, 403, 413, 435–436, 463, 465, 693
- deconvolution, 495, 570, 594, 681, 691, 699, 704, 706, 708, 716, 724–725, 729, 735
- definite integration, 45
 of derivatives property, 45, 63

- degree of aliasing, 253, 462, **467**
- degrees Kelvin, 198
- Dembski, William A., vii
- demagnify, 145
- demodulation, 122–125, 134, 204, 268, 740
- deMoivre
Abraham, 518
-Laplace theorem, 190
- derivative. Also see – bounded derivative & fractional derivative Hilger derivative & kernel, xii, **262**, 264–265, 307
function, 156
interpolation, **261**, 263, 265, **306–308**, 715
of a bandlimited signal, 261, 263, 307
of a bounded function, 101–102
of a discontinuity, 65
of a finite energy function, 101
of the cone kernel, 441, 444
of the characteristic function, 155, 168, 205
of the Dirac delta, 232
of the output, 137
of the second characteristic function, 156, 162
of the sinc, xii
property, 45, 63, 205
samples, 276, 281, 303–304, 306
sampling, 302, **304**, 306
theorem, **18**, 45, 65, 71–72, 86, 102, 141, 154, 192, 232, 262, 347, 401
- DeSantis, P., 477, 695
- Descartes, Rene, 242, 695
- Description de l’Egypte, 5–6
- detection theory, 203, 677–679
- deterministic
autocorrelation, xi, 15, 317, 457
correlation, 15, 457
random variable, **168**, 177
- DFT, ix, 13, 50, **52–57**, 60, 72, 103, 118, 125–126, 359–360, 366, 485, 681, 686, 695, 731, 739. Also see – discrete Fourier transform
leakage, **55**
- diagonal
elements, 399
matrix, 337, 340, 359, 377, 549
- diamond kernel, **431–432**, 444, 721
- diapason, 614
- diapente, 614
- diatesseron, 614
- dice, 151, 602
- die, 151, 169, 177, 602
- difference equations, 8, 59–60, 523, 646–648, 650, 652, 655, 704, 726
- diffraction, 3–4, 7, 495, 623, 626–627, 629–631, 633–639, 641, 657, 659, 681–682, 684, 697, 700, 703, 706, 710, 714, 719, 722, 735, 740–741
integral, 624, 631, **633–635**, 710
- digital integration, 311
- diffraction intensity, 63
- differential equation – see linear differential equation
- digital
signal processing, ix, 52, 683, 693–694, 729.
Also see DSP
versatile disc, ix. Also see DVD
video disc, ix. Also see DVD
- dilation, xi, **570–573**, 575–576, 578–580, 582, 590, 593, 608
duality, 576, 578–580
subset property, 579, 582
- dimple, 576
- diodes, ix, 106, 687
- Dirac delta functions, vi, xii, **20–23**, 31–32, 54–55, 64–66, 83–84, 110, 112–114, 120, 139, 145, 168, 178, 199, 221–222, 232, 283, 356, 373, 429, 443, 456, 458, 542, 588, 592, 626, 627, 640
- Dirac delta scaling, **21**
- direct interpolation, **246**, 296
- direction cosines, **627–628**, 630, 657
- directly sampled signals, **271**, 278, 293
- Dirichlet
conditions, **17**, 67, 219
Johann Peter Gustav Lejeune, 17
- discontinuous function, 477, 682, 688, 729.
Also see – continuous function
- discrete
cosine transform, ix, 4, 6, **56**, 360, 527, 726–727. Also see – DCT
Fourier transforms, ix, 10, 13, **52**, 125, 359, 440, 485, 681, 686, 695–696, 710, 731, 735, 738. Also see – DFT10, 11, 46, 599
periodic nonuniform decimation, **463**, 465
time convolution, 13, 51, 81, 118, 231, 236, 250–251, 469, 603
time Fourier transforms, ix, 10, 13, **50–51**, 54, 154, 587. Also see – DTFT
time periodic signals, 119
time scale, **586–588**, 592, 603
time signals, ix, xii–xiv, 7, 11–12, 59, 72, 126, 236, 416, 419, 463, 503, 564, 583–584, 586–587, 692, 706, 722
time system, 72, **113**, 115, 135–136, 139, 141–142, 698, 720
time windows, 413
uniform random variable, **169–170**
- discretized
intensity, 546
kernel, 547
- discriminant, 85, 610–612
- dispersion, 155, 157, 174, 177
- displaced, 14, 255
- displacement, 399, 616
assumption, 611
vector, 504, 513
- dissipated power, 11

distribution, vi, xii, 20, 151–152, 154, 168, 173–174, 189, 202, 232, 407, 417, 431, 433–435, 537, 551–553, 557, 560–561, 665, 692–683, 686–687, 689, 692, 696, 699–700, 702, 704–706, 709, 711–713, 721–723, 725–727, 735, 738–741, 743–744

distributive, 115–116, 580, 595, 608

dose, 547, 549, 554, 557–558, 560–561, 692

 constraint, 547–549, 554

 contour, 557, 560–561, 735

 distribution, 557, 560

 domain, 547

 matrix, 554, 558

 prescription, 546

 synthesis, 546, 556–557, 560–561

 vector, 547

double

 diamond kernel, 432, 434, 721

 factorial, xiii, **35**, 63, 206

 Mersenne primes, 662

doublet, 232

Dougherty, Edward R., 609, 700

DSP, ix, 644. Also see – digital signal processing

DTFT, ix, **13**, 50–53, 55, 59–60, 82, 142, 359, 368, 466–467, 472, 587. Also see – discrete time Fourier transform

duality theorem, 15, 19, 21, 78, 86, 127, 140, 474

duration limited signals, 495, 507–508, 515, 688, 733

duty cycle, 448, 450, 453, 455, 458–459, 461, 463

DVD, ix, 4

dynamic

 signal, 411

 systems, 106, 694, 704, 526

Dyson, Freeman, 570

E

École Normale, 5

École Polytechnique, 5

Eddington, Sir Arthur, 610, 696

edge detection, 576–577

Edwards, Jonathon, 217, 696

Egyptology, 6

eigenvalues, xiii, 473, 475–476, 481, 492, 523–526, 663, 685, 701, 708, 711, 731

eigenvectors, 523, 663

Einstein, Albert, 17, 104, 151, 288, 696

El-Sharkawi, Mohamed A., viii, 532, 534–536, 538–543, 716, 723

electric

 field amplitude, 624, 627, 629–631

 field wave equation, 626

electromagnetics, 3–4, 112, 690–691

electromagnetic

 signal, 644

 propagation, 624

 wave, 482, 610, 705

engineering, 3, 6, 646, 731

 bioengineering – see bioengineering

 engineering

 biomedical – see biomedical engineering

 communications – see communications engineering

 math, 20

 microwave, 624

entire functions, 219, 685, 692, 711, 727

envelope, 124–125, 133, 204, 216, 276, 320–321, 326

 demodulation, 124

 detection, 125, 204, 276

 detector, 124, 133

equal to by definition, xi, 14

Erlang random variable, 153, 162–164, 175, 190, 201, 205

erosion, 573–575, 578–581, 584, 595, 608

 duality, **578–579**, 581

 subset property, **579–580**, 584

errata, viii

error

 absolute – see absolute error

 bound, 320, 720, 726, 742

 curve, 525

 free, viii, 684, 717

 interpolation – see interpolation error

 magnitude, 225

 mean square – see mean square error

 normalized – see normalized error

 plot, 518

 quantization – see quantization error

 round off – see round off error

 range, 530

 truncation – see truncation error

Euclidean, 327–328, 404, 724, 731

norm, 404

Euler's

 formula, **21–22**, 24, 29, 32, 42, 61, 97

 head, 520

Euler, Leonhard, 519, 530, 687

Euler-Mascheroni constant, xii, 675

even, xii, 10, 12–13, 21, 24, 25, 32, 45–46, 61, 63, 65, 81–83, 86, 88–90, 92–94, 96, 99, 139, 162, 168, 207–208, 259, 262–264, 278, 282–284, 286, 292, 304, 310, 345, 386, 420, 432, 435, 441, 444, 457, 472, 563, 567, 596, 616

 functions, xii, 13, 45–46, 65, 81–82, 92–93, 162, 345, 420, 457. Also see – even signal

 function property table – see tables

 moments, 168

 periodic function, 457

 signal, 12–13, 563, 567. Also see – even function

 signal property table – see tables

 window, 432

evenly odd functions, 69, 88, 96, 138, 149

expectation, **152**, 314, 316–317, 384
 expected value, xii, **152**, 157, 177–179, 194, 214, 289
 exponential, 19, 29, 115–116, 121, 153, 160–162, 164, 171, 175, 203, 208, 419, 633, 635, 667, 679, 684, 692, 695, 698, 722, 732, 736, 739
 decay, 679, 684
 random variable, 153, **160–162**, 164, 175, 667
 Taylor series, 171, 208
 extensive, **581**, 583, 608
 extrapolation, 8, 328, **447–449**, 462, 473, 475–480, 482, 484–486, 492, 495, 515–516, 684, 689–691, 698, 705–706, 708, 710, 712, 715–716, 723–724, 728, 731, 738–739
 algorithm, **462**, 691, 706, 715–716
 matrix, **484–485**, 708, 728
 extrema 17, 65, 67, 91–92, 98–99
 of yield, **650–651**
 extreme value random variable, **675**

F

F random variable, **673–675**
 fading, **124**, 133
 Family, 360–361
 far field, 4, 8, 624, 635–636, 643–644, 691
 Faraday, Michael, v, 518
 fast Fourier transform, ix, 9, 52, 360, 686, 693, 704, 724. Also see – FFT
 fault diagnosis, 424, 741
 feature extraction, 424, 713
 FFT, ix, 9, 52, 126, 360, 373, 436, 438, 690, 733, 744. Also see – fast Fourier transform
 filter, ix, 4, 7–9, 59–60, 107, **120–124**, 125–126, 131, 134–135, 142–143, 199–200, 204, 215, 222, 227, 236, 242, 245, 247–250, 252–253, 256–259, 268, 270, 274–275, 278–280, 283, 286, 290–296, 298–301, 306–308, 311, 313–316, 318–319, 322–324, 327, 351–352, 360, 366–371, 373, 385–386, 397, 402, 413–415, 418–424, 436, 438, 439–442, 451, 455, 462, 470, 473–474, 477–478, 489, 507, 516, 537, 603–604, 680–681, 683–684, 687, 691, 693–694, 697–698, 700–701, 703–705, 709–714, 716–723, 725–726, 728–729, 732–738, 740
 bank, 9, **413–415**, 439, 683, 698, 712, 719, 734, 737
 filtered
 back projection, **352**
 interpolation, 291–292, 306, 322
 NINV, 298–300
 projection, **351–352**
 signals, **250**, 252, 315
 finance, vii, 6–8, 60, **646–647**, 658

finite
 area, xiii, xviii, **11**, 17–18, 64–65, 71, 84, 86, 100–101, 111, 167–168, 224, 231–232, 430, 542
 area constraint, xiii, **430**, 542
 energy signals, xiii, **11**, 20, 39, 48–49, 61, 65, 71–73, 84, 100–101, 217, 224, 231, 235, 239–240, 243, 277–278, 323, 448–449, 474, 493, 502–503, 686, 707, 725, 733
 impulse response, ix, 59, 419, 603. Also see – FIR
 support, 253, 473
 FIR, ix, 59, 327, 366, 419, 603–604, 691, 718, 720, 726, 728, 732, 736. Also see – finite impulse response
 first. Also see – first order
 derivative, 156, 160–161, 164, 205, 207, 263, 303, 512
 difference, 512
 fret, 623
 harmonics, 613–618
 moment, **155–156**, 167, 671
 orthant, 517
 overtone, 623
 quadrant, 399
 subharmonics, 620
 year graduate student, vi
 first order
 aliasing, 451, 456, 459, 461, 483
 decimated sample restoration, **390**, 392, 493
 difference equation, 8
 spherical Bessel function, 263
 spectrum, 483
 statistics, **193–194**
 Fisher-Tippett random variable, **675**
 fixed point, 498, 516, 559, 562–563
 Flatland, 326, 680
 flip
 a coin, 151, 169
 and shift, **117–118**, 333, 337
 flute, 234
 FM, ix, 67, 717, 740. Also see – frequency modulation
 for all, **xi**, 11–12, 31, 33, 49, 61, 73, 77, 107, 109, 113, 120, 125, 128, 139, 142, 149, 153, 157, 195, 200, 231, 232, 266, 299, 354, 388–389, 403, 429, 465, 496, 499, 501, 503–504, 507, 517, 546, 558, 563, 566, 569, 579, 581, 586, 590, 600, 616
 forward difference, 587
 Fourier
 acoustics, 3, 740
 analysis, vi, 3–4, 6–8, 151, 221, 262–263, 416, 458, 570, 583, 695, 698, 708, 711, 731
 array imaging, 3
 - Bessel transform, 343, 345

Fourier (*cont'd*)

- coefficient, 4, 16, 50, 69–79, 92, 95, 98, 143, 223, 238, 265–266, 276, 283, 323, 357–358, 370, 485, 685, 729. Also see – Fourier series coefficient
- complex – see complex Fourier transform
- descriptors, 3, 712
- Edmie, 4
- integral, 3, 10, 723, 736
- inversion, 3, **19**, 235, 241, 730, 733. Also see – inverse Fourier transform
- Jean Baptiste Joseph, **3–6**, 518, 610
- Joseph (senior), 4
- kernel, 235
- transform matrix, 485
- transform nuclear magnetic resonance, 3, 720
- optics, 3, **624**, 639, 697, 700, 734
- reconstruction, 3, 733
- series, vi, 3, 5, 7, 9, 10, **13–17**, 31, 37, 48–51, 60, 67–70, 92–94, 100, 143, 150, 197, 200, 214, 219, 221–225, 274, 303, 327, 335, 342, 344–345, 352, 356–359, 370–371, 373–374, 402, 408–410, 420, 450, 453, 460, 466, 474, 485, 510, 612–613, 681, 687, 689, 692–696, 703, 706, 710–711, 719, 724–725, 730, 735–736, 739, 743–744
- series coefficient, 14, 31, 60, 67, 93–94, 342, 358, 370, 402. Also see – Fourier coefficient
- spectra, 3–4, 704–705
- spectrometry, 3
- spectroscopy, 3, 702, 737
- theory, 3, 704, 739
- transform, vi–vii, ix, xi–xii, 3–4, 6–10, **13–15**, 18–20, 22, 22–25, 26–32, 34–35, 37, 39, 41, 43–47, 49–52, 54–56, 58, 64–69, 72, 76–78, 81–83, 89, 91, 94, 101, 107, 109–110, 115–116, 120–121, 124–129, 131–133, 136–139, 141, 143–144, 148, 149–154, 160–162, 174, 190, 196, 199–200, 203, 210, 213, 221, 223, 230, 240–241, 249, 251, 253, 269, 273, 287, 291, 315, 327, **330–336**, 340–346, 348–351, 359–361, 373–376, 396–401, 404, 406–407, 411, 413–419, 422–423, 425–426, 428, 435–436, 438–441, 443, 450, 457–458, 460, 474, 477, 482, 485–486, 507–508, 511–512, 516, 566, 568–569, 573, 583, 587–589, 591–592, 597, 601, 623–624, 626–628, 630, 636–638, 641–646, 657, 659, 680–687, 689–690, 693–697, 700, 702–706, 708, 710, 712–713, 716, 718, 720, 722, 724, 726–728, 730–732, 734–735, 738–743
- transform nuclear magnetic resonance, 3, 720
- transformer, 107, **109–110**, 131, 133, 136, 143–144, 638
- transform tables – see tables
- vision, 3, 738

Fox, Warren L.J., viii, 716, 725

fractional

- derivatives, 8, **401**, 722
 - Fourier transform, xii, 6, 8, **126–129**, 138–139, 148–150, 680, 684, 689, 690, 697, 706, 708, 710–711, 713, 718, 722, 724, 726, 728, 734, 741–743
- Franklin, Benjamin, 519
- Fraunhofer
- approximation, **633–636**
 - assumption, 635
 - diffraction, 4, 624, **635–637**, 641, 657, 659, 684
 - Joseph von, 519
- frequency, vii, ix–x, xii, xiv, 4, 6–7, 12–14, 19–20, 47, 50–51, 53–55, 60, 64, 67–68, 115–117, 120–124, 126, 133–135, 142, 196–200, 217–218, 220–222, 225, 234–236, 249, 252, 256, 267–268, 275–277, 283, 290, 295, 304, 306, 327, 341–342, 345–346, 348, 351, 360, 365–367, 369–370, 372, 385–386, 389, 402, 411–425, 427–430, 432–437, 439, 441, 447, 450, 454, 467–468, 472, 477, 482–483, 495, 532, 537, 539, 541–542, 551–553, 566, 588–589, 610, 612–616, 618–623, 625–626, 628–630, 636, 647–648, 651, 656–658, 680, 682–685, 689, 691–696, 699–700, 702–703, 705, 708–713, 716–723, 725, 727–728, 732–734, 736, 738–741, 744
- deviation, 68, 614
- domain, 6, 19–20, 51, 53–55, 123, 199, 222, 268, 341, 385–386, 389, 416, 428, 441, 447, 450, 454, 468, 477, 682, 708–709, 740
- marginal, **427–428**, 537, 542
- modulation, ix, **67**. Also see – FM
- resolution, 7, 416–418, 428, 435–436, 438, 537, 539, 541
- response, 60, **115–116**, 120–121, 135, 142, 200, 249, 252, 256, 275, 351, 366–367, 369–370, 372, 402, 719
- Fresnel
- approximation, 633–635, 639
 - diffraction, 624, **633**, 635–636, 638–639
 - integral, 634
 - Augustin Jean, 518
 - Fraunhofer boundary, 636
- fret, 617–618, 621–623
- bar, 617–618, 622–623
 - calibration, **621**, 623
 - spacing, 622
- full
- modulation, 216
 - rank matrix, 506, 517, 547
- fundamental frequency, 411, 414, 612–614, 621
- fuzzy
- convex sets, 500
 - linguistic variable, 500

G

Gabor, Dennis, 424, 699
 gamma
 function, xii, **35–36**, 141, 163
 random variable, 153, **161–164**, 175, 190, 201–202, 205–206
 random variable moments, 201, 205
 Gauss, Johann Carl Friedrich, 518
 Gaussian, xii, 8, 30–31, 43–44, 64, 138, 149, 153, 155, 159–162, 166–167, 175, 178–179, 186–192, 201–203, 207–208, 211, 318–319, 343, 407, 518, 667–669, 676–679, 682, 696, 699, 703, 708
 asymptotic – See asymptotic Gaussian function, **30–31**
 jitter, **318**
 noise, 20, 518, 682, 699, 708
 random variable, **159–162**, 166, 175, 179, 187, 189, 201, 207, 407, 667–669, 677–679
 ratio random variable, **166**
 generalized
 Cauchy random variable, **678–679**
 comb function, **70–71**, 720
 Gaussian random variable, 161, **677–679**
 interpolation, **242**, 248, 274, 380, 704, 722
 time-frequency representation, ix, 417, **424**, 436, 721, 744. Also see – GTFR
 genius, 3
 geometric
 mean, 439, 620, 622
 random variable, 175, 203
 series, 9, 26, 32, 34, 62, 74, 90, 144, 146, 169, 229, 267, 291, 312, 442, 446, 480, 486, 489, **662–623**
 geophysics, 424, 434, 495, 680
 Gerchberg, R.W., 477, 700
 Gerchberg-Papoulis algorithm, see Papoulis-Gerchberg algorithm
 Gerchberg-Saxton algorithm, 566, 568, 691, 699–700, 705, 728, 731, 739–741
 Giardina, Charles R., 609, 700
 Gibb's phenomenon, 9, **17, 70**, 100, 225, 707
 Gibbs, J. Willard, 17
 Glad Man image, 568–569
 global maximum, 236
 God, v, 104, 151, 126, 411, 447, 570, 693, 728
 Goertzel's algorithm, 6, 52, **125–126**, 440, 442
 Goldbach's conjecture, 596
 Goldburg, Marc H., viii, 700
 Gori, F., 477, 695, 701
 graininess, **586**, 597–601, 605
 Gravagne, Ian A., viii, 583, 694, 702, 716
 gray scale images, 137, 180, 362, 364–366, 527
 greedy limit cycle, 499–500
 Green's function, 112, 333, 624
 greenhouse effect, 6
 group delay, 430

GTFR, ix, 7, **424–432**, 434–439, 441, 443–444, 537, 539, 543. Also see – generalized time-frequency representation
 table – see tables
 kernel, 425–432, 436, 537, 539, 543
 mechanics, **425**
 Gubin, L.G., 495, 702
 guitars, 613, 617
 Gumbel random variable, **675**

H

Hagler, Marion O., viii, 702, 715
 Haldeman, Douglas G., viii, 715
 half
 Gaussian random variable, **668**
 normal random variable, **668**
 step, 613
 tones, 411
 Hall, Michael W., viii, 70, 715
 Hamming
 filter, 107
 window, 415, 420, 422
 Richard W., 10, 104, 306, 703
 HandbookOfFourierAnalysis.com, vii
 Hankel transforms, xii, 134, 226, **343**, 345, 400–401, 406, 680–681, 702, 704, 707, 709, 719
 Hann window, 415. Also see – Hanning window
 Hanning window, 56, **415**, 420, 422–423, 544
 harmonics, 8, 344–345, 401, 610, **612–623**, 625, 632, 657, 686–687, 689, 694, 695, 699, 709, 742
 Hartley transform, xiv, **57–58**, 72, 686, 703, 743
 Hawking, Stephen, vi, 151, 703
 Heisenberg's uncertainty principle, vii, 7–8, 192, 416, **645–646**, 657, 704
 Healthy Girl image, 529–530, 534–536, 540, 542–543
 HeNe laser, 637
 Hermetian, 45, 196, 200, 204, 235, 239, 267, 366. Also see – conjugate symmetry
 Hermite
 polynomials, xii, 9, **43**, 68–69, 96, 138, 149
 Charles, 447, 519
 - Gaussian function, xii, **43–44**, 138, 149
 Hertz, **12**, 14, 68, 218, 234, 236, 411, 482
 Heinrich, 10
 heteroassociative memory, **527**
 heterodyne, 122, 124, 133, 268–269, 277, 283
 heterodyned sampling, **268**
 hexagon, 345–355, 376–379, 385–387, 719
 Higgins, John Rowland, 218, 689, 704
 higher transcendental function, 6. Also see – transcendental function
 higher order
 DFT's, 360
 decimation, **393–395**
 kernels, 263
 derivatives, 449

- higher order (*cont'd*)
 derivative sampling, **259**
 harmonics, 617
 spectra, 380
 terms, 315, 643
- high pass filters, **121**, 135, 204, 271, 360, 369–370
- Hilbert
 David, 120, 519
 spaces, vi, 328, 501–503, 515, 684, 643
 transforms, 8, **46**, 60, 64–65, 77–78, 133, 140, 228, 230–231, 252, 270, 272, 270, 280, 351, 370, 372, 716, 734, 743
- Hilger
 derivative, 586–587
 integration, 587
 Stefan, 583, 704
- holography, 495, 427, 687, 690, 693, 699–700, 706, 713, 715, 725, 731, 735–736, 740
- homogeneity, 112–113, 630, 739
- homogeneous systems, 9, **104–105**, 108–111, 135, 142, 625, 630, 690, 721–722, 724
- horizontal, 337, 398, 403, 528, 559, 561–562, 565
 axis, 412, 527, 551, 591
 derivative, 146, 147
 flip, 337
 forces, 611
 line, 620, 622, 436
 motion, 138
 movement, 611
 projection, 349
 scaling, 337
 slice, 350, 397
 swath, 418
 tension, 610
- Howard's minimum-negativity-constraint, 493, **516**, 691
- Howard, S.J., 516, 704–705
- Huffman coding, 365
- hyperball, 328
- hyperbolic
 cosecant, **24**. Also see – cosech
 cosine, **24**. Also see – cosh
 secant, **24–26**, 161–162. Also see – sech
 secant random variable, **161–162**
 sin, **24**. Also see – sinh
 tangent, **24**
 trig functions, **24–26**
- hypercube, 291, 328
- hypergeometric function – see confluent hypergeometric function
- hyperplane, 446, 503–504
- hypersphere, 328, 379, 386, 402, 408, 410
- I**
- ideal gas, 401, 407
- idempotent, ix, 497, 501, 506, 583, 595, 603, 608
- identical middles, ix, **513**, 515–518, 520, 522, 530
- identically distributed, 157, 176, 314
- identity
 element, 115
 for Laplace transformation, 229
 matrix, 359, 506
 operator, 591
 vector, 625
- iff, **xii**, 57
- IIR, ix, **59**, 135, 142, 419–423, 440, 442.
 Also see – infinite impulse response
- ill-conditioned, 298–299, **663–664**
- ill-posed, 8, 137, 248, 250, 259, 302–304, 306, 323, 449, 462, 477, 482, 485, 492, 516, 684, 691, 736
- ill-posed sampling theorem, 304, 691
- IM, ix. Also see – see identical middles
- image
 averaged – see average image
 binary – see binary image
 block, 365–366, 532, 534–536, 538–539, 541–543, 723
 coding, 360
 compression, 6–7, 57, 327, 360, **362**, 364, 495, 527
 encoding, 4, 362–363
 JPEG – see JPEG
 library, 517
 optical – see optical image
 processing, vi, 3, 495, 570, 575, 681, 690–691, 700, 706, 721, 730, 733
 restoration, 366, 495, 723, 727, 730, 742
 samples, 385, 691
 synthesis, vii, **495**
 thresholded – see threshold image
 vector, 533
- imaginary operator, 229
- imaging, 3, 106–107, 112, 327, 377, 533, 544, 624, 638, 640–642, 681–682, 684, 686–687, 691, 694, 700–701, 705–709, 719, 723–724, 728, 732, 735, 737, 743
 aperture, 533, 544
 system, 106, 377, 624, 638, **640–642**, 682, 701, 705, 709
- implicit sampling, **277**, 682, 697
- impulse
 kernel, 127
 response, ix, xii, 59, 107, **112–118**, 120–122, 125–126, 130–131, 133, 135–137, 139, 142–143, 146, 148, 150, 196, 198–199, 248, 333, 366–368, 418–421, 423, 440, 603, 631–635, 716
- incoherent illumination, 377, 706
- incomplete
 cosine, 262
 sine, 262
- independence, 157

- independent, 9–10, 15, **157**, 159, 166, 168, 174–176, 179, 195, 203, 219, 264, 289, 310, 315–316, 342, 401, 447, 477, 499, 558, 601, 617–618, 668, 671, 673
and identically distributed, 157. Also see – i.i.d.
random variables, 159, 174, 179, 401, 671
i.i.d., 157, 162, 170, 176, 186–187, 189, 202–203, 211, 667, 671. Also see – independent and identically distributed
- index, vi, 41, 48, 53, 95, 310, 474, 501, 517, 619, 639, 688, 705, 711, 722
- induction, 145, 205, 481, 492
- infinite
area, 86, 167–168
mean, 9
energy, 20, 84, 100, 224, 322
height, 21, 23, 120
impulse response, ix, 59, 135. Also see – IIR
mean, 665
moment, 168, 202, 209, 671–672
noise level, 84, 304, 324
number, 84, 231, 272, 288, 320, 328, 385, 387, 570
power, 120, 197
series, 300
sum, vi, 62, 294, 484, 485
variance, 665
- inflation, 647, 651–652, 658
- initial condition, 60, 523, 617–618, 648, 655, 663, 670
- inner product, 47, 273, 502–503, 533
- inside boundary, 576
- instantaneous frequency, 68, 430
- integral
theorem, 87
transform, 72, 226–227, 273, 695, 697, 707, 710, 715, 725, 743
- integrating detector, **250–251**, 276
- integration
by parts, 311
of derivatives property, 45, 63, 205
limit, 158, 306, 346, 488
order, vii, 19, 432
over a period, 14–15
over a unit interval, 50–51
region, **380–381**, 383, 385
- integrator, 441
- intensity
modulation, 558
of light, 636
of field amplitude, 636
of the far field, 636
profile, 558–559, 561–562
- interest rates, 649–652, 654–656, 658
- interference
bandwidth, 429
suppression, 429, 726
- interior point, 497, 504
- interlaced
sampling, 252, **257–258**, 303–306
signal-derivative sampling, **304**, 306
- interpolation, vii, 6, 8, 50, 217, 219–220, 222, 225–226, 232, 242–243, 245–249, 252, 256–261, 263, 265–267, 271–278, 281, 284, 287–297, 301–308, 310–316, 322–323, 375, 380–381, 383, 385, 391–392, 397, 402–403, 447–450, 456, 461, 463–465, 467, 470, 473, 476–477, 480, 485–486, 495, 680–681, 685, 688–689, 693–694, 697–698, 702–704, 706–712, 715–717, 721–724, 726, 729–733, 735, 738–740, 742–743
- error, 288, 314, 477
- formula, 219, 222, 245, 247, 261, 306, 315, 738
- function, 8, 225, 242, **247–249**, 252, 256–261, 266–267, 271–278, 284, 287, 294–295, 297, 304–305, 322, 375, 380–381, 385, 392, 397, 403
- kernel, 391
- noise, 243, 261, 289–293, 295–296, 302–304, 306–307, 310, 312–313, 315, 322, 323, 402, 456, 461
- noise level, 289–292, 295, 303, 306, 310, 322, 402, 461
- noise power spectral density, 291
- noise variance, 293–294, 296, 302–304, 306–307, 312–313, 315, 323, 461
- theory, 6, 217, 697, 716, 739
- interval interpolation, 447, **463–464**, 473, 476–477, 480, 485–486, 716
- invariant – see shift invariant & time invariant
- inverse – also see inversion
Abel transform, 401, 402, 407
bounded – see bounded inverse Fourier transform
cosine transform, 65
DFT, **53–54**, 57, 72, 103, 118, 359, 362, 366, 485
DTFT, 142
filter, 27, 279–280, 313, 316, 319
FFT, 373
Fourier transform, **14**, 19, 45, 47, 64, 77, 83, 94, 121, 144, 174, 200, 213, 249, 273, 287, 350, 360, 375, 395, 406, 441, 443, 486, 601, 626–628, 630, 642
Hankel transform, 406
Hilbert transform, 46, 140
pseudo – see pseudo inverse
quantization, 365
Radon transform, 345, 349, **351–352**, 533
transposition, 340
- inversion, 14, 15, 50–51, 83, 107, 330–331, 400, 480, 684, 729. Also see – inverse
formula, 223, 238, 250, 406
of the DFT, 103
system, see invertible system

inversion (*cont'd*)
 theorem, **19**
 Fourier – see Fourier inversion
 invertible system, **107**, 109–110, 136,
 142, 144
 irrational
 number, 601, 605, 613
 time scale, **601**
 isoplanatic systems, 106, 333, 404, 630–631
 iteration relaxation, **558**

J

Jack image, vii, 575
 Jacobi, Carl Gustav Jacob, 242, 519–520, 530
 Jacobian, 340
 Jeremiah image, vii, 180
 Jesus Christ, v
 jinc function, xii, 23, **37–38**, 63–67, 76–78,
 88, 91, 132, 139, 343–344, 358, 385,
 406, 637
 jitter, xiv, 288, **313–316**, 318–319, 323, 681,
 687–688, 699, 712, 725
 density, xiv, 318
 offset, 313
 jittered samples, **313–314**, 316, 318
 John the Baptist, 5
 Johnson-Nyquist noise, 197
 Joint Photographic Experts Group, ix, 362, 708.
 Also see – JPEG
 joint probability density function, 157, 316
 Josh image, 360–361
 Joshua image, viii, 580
 JPEG, ix, 4, 57, 362, 527, 681, 708, 731.
 Also see – JPG
 JPG, ix, 7, 327, 362. Also see – JPEG

K

Kaiser window, 415
 Kaplan, Dmitry, viii, 708, 715
 Kelvin, Lord, 3, 518, 736. Also see – Thomson,
 William
 kernel, x, xii, 72, 128, 226–227, 230, 235,
 241, 262–265, 274, 284, 307, 333, 391,
 424–438, 441, 444, 456, 537, 539,
 543–544, 547, 551–553, 631, 692–694,
 696, 699, 701, 707–709, 711–712, 721,
 725, 738, 741–742, 744
 constraint, 626, 628
 synthesis, 433–435, 438, 537, **543**,
 551–553, 721
 Kirkwood-Rihaczek distribution, 431
 Kotelnikov, Vladimir A., 218–219
 Kral, E. Lee, vii, 702
 Kramer's sampling theorem generalization,
 6, 50, 218, 239, 242, **273–274**, 278, 699,
 706–707, 710, 716, 743
 Kramer, H.P., 6, 50, 218, 242, 273, 278, 239,
 706, 710
 Krile, Thomas F., viii, 445, 702, 708, 715

Kronecker
 delta, xii, **27**, 113, 128
 delta sifting property, **113**, 128
 Leopold, 570
 Kuterdem, H.G., viii, 692

L

L'Hopital's rule, 33, 649, 661
 L'Hopital, Guillaume François Antoine Marquis
 de, 518
 Lacroix, Sylvestre, 5
 Lagrange, Joseph-Louis, 5–6, 218, 518
 Lagrangian, 242, 272, 277, 284
 kernel, 284
 interpolation, 242, **272**, 277, 717, 726, 743
 Lanczos window, 415
 Langer, Rudolph E., 3
 Laplace
 autocorrelation, **198**, 291–292, 309, 311–312,
 460–464
 jitter, 318
 noise, 161, 203, 694, 715
 Pierre-Simon, 104, 518
 random variable, **161**, 678
 transform, xiv, **18**, 58, 64, 134, 141,
228–230, 694
 Laplacian, **628**, 631
 Larson, John N., viii, 715
 laser, 630, 637, 705, 710, 713, 722
 lattice
 Bravais – see Bravais lattice
 type, **154**, 170–171, 601
 law of large numbers, 6, 158, **177–179**
 Laybourn, Loren, viii, 716
 leakage, **55–57**, 415
 leakage-resolution tradeoff, **415–416**
 Lebesgue
 Henri Leon, 519
 integral, xiii, 104, 739
 measurable, xiii, 11, 104, 502
 LED, ix, 4
 Lee, Shinhak, viii, 545, 554, 556–557,
 559–562, 692
 Legendre
 polynomials, xiii, 9, **40–41**, 50, 68–69,
 88–89, 94–96
 Adrien-Marie, 519
 Leibniz's rule, 92, 444, 644, **661**, 722
 Leibniz, Gottfried Wilhelm, 447
 Lenore image, 582
 lenses, xii, 377, 624, 638–643 710, 738
 lens law, **640**
 Leonardo da Vinci, 518
 library
 matrix, 516–517
 subspace, 520, 522, 530–531
 vector, 516–518, 525–527
 lightning, 10, 161

- limit
 cycle, 499–500, 543
 point, 498
- Linden, D.A., 252, 259, 713
- line
 sample, **397**, 403
 spread function, 112, 333, 682, 715
- linear
 array, 547, 701
 chirp, 439, 544
 convergence, **523**, 531
 convolution, 118–119
 differential equations with constant coefficients, 135
 integral transform, 72, **226–227**, 715
 manifold, 503, 517
 motion blur, 8, **137–138**, 146
 systems, 6, **105**, 112–114, 129–131, 133, 136, 139, 143, 150, 196, 198, 330, 682, 700–701, 713, 715, 724–725
 time invariant system, x, **106**, 112, **114**, 142, 439. Also see – LTI
 varieties, x, **504**, 507, 509–511, 513–518, 520, 522, 530–531, 533, 563
- loan, 647, **655–656**
- log normal random variable, **669–701**
- log-Weibull random variable, **675**
- logistic random variable, **672–673**
- long
 column vector, 532
 duration, 418
 history, 424
 period of time, **656**, 417–418
 window, 417. Also see wide window
- loose conditions, 179. Also see – mild conditions
- Lord Kelvin – see Thomson, William
- lost
 block, 7, 530
 image blocks, 527
 information, 532
 pixel, 527
 sample, 7–8, **243–247**, 272, 275, 278, 286, 294–296, 296–302, 323, 327, **382–387**, 402, 486–487, 715, 738
 signal interval, 447
 through dilation, 576
- lower
 bound, **308–312**, 512
 frequency, 267, 283
 limit, 439
 sideband, 133
- low pass
 filter, ix, 4, 107, **120–121**, 123, 135, 143, 222, 227, 236, 245, 268, 274, 307–308, 369–370, 373, 418, 451, 455, 470, 473–474, 478, 485, 507, 516, 537, 701. Also see – LPF
 filter operator, 478
 sense, 12, 219, 227
 signal, 124, 271, 291, 294, 687
 trigonometric polynomial, 266
- low passed kernel, ix, **227**, 230, 235, 241. Also see – LPK
- lower sideband, 133
- LPF, ix, **123**, 279, 308. Also see – low pass filter
- LPK, ix, 227, **229–230**. Also see – low passed kernel
- LTI systems, x, **106**, 109–111, 114–118, 120, 125–126, 129–131, 133, 136–137, 139, 142, 198–200, 204, 418–419, 440. Also see – linear time invariant system
- Luke, H.D., 218, 713–714
- Luther, Martin, 411
- LV, x. Also see – linear variety
- ## M
- magnification, 108–109, 337–338, 636, 640, 735
- magnifier, **107–109**, **130–131**, 136, 144, **404**
- magnify, 108, 475
- major chord, 613, 616, 618–620
- major scale, **618–620**, 636
- Mann, Thomas, 217, 714
- mantissa, 76
- Margenau-Hill distribution, 431, 714
- marginal, **427–428**, 441, 537, 541–544, 552–553
 density, 401
- marginally stable, 420, 441
- Markov, Andrei Andreyevich, 519
- Marks
 Connie Lynn J., viii
 Jeremiah J., viii
 Joshua J., viii
 Lenore, viii
 Marilee M., viii
 Ray A., viii
 Robert (Jack), viii
 Robert J., II, iii, 219, 433–436, 445, 495, 532, 534–536, 538–543, 551–554, 557, 559–562, 642, 691–692, 684, 700, 702–704, 708, 712, 715–716, 721, 734, 726, 731, 740, 744
- Masquerade image, 529, 538–539
- mass density, 611, 622
- matrix
 condition number – see condition number
 diagonal – see diagonal matrix
 equation, 276, **505–507**
 extrapolation – see extrapolation matrix
 full rank – see full rank matrix
 idempotent, 506
 identity – see identity matrix
 ill conditioned – see ill conditioned
 inverse, 664
 library – see library matrix
 offset – see offset matrix
 of integers, 402

- matrix (*cont'd*)
 on ones and zeros, 533
 of zeros, 468
 operation, 452
 nonsingular, 336
 periodicity – see periodicity matrix
 projection – see projection matrix
 quantization – see quantization matrix
 rotation – see rotation matrix
 sampling – see sampling matrix
 scaling – see scaling matrix
 singular – see singular matrix
 square, 405
 sub – see submatrices
 - vector, 53, 226, 230, 468
- mathematical morphology, vii, 7, **570**, 703.
 Also see – morphology
- mathematicians, vi, 5, 411, 519, 530–531
- Matheron, Georges, 570, 718
- maximally packed
 circles, 377–379, 393–394, 403. Also see –
 maximally packed spheres
 spheres, 380. Also see – maximally packed
 circles
- maximum
 deviation, 528, 657
 dimension, 635–636
 energy, 485, 493
 error, 366
 filter output, 215
 frequency component, 277, 427
 lens thickness, 639
 number of vectors, 526
 pixel value, 569
 power, 204
 value, 12, 33, 178, 236, 558
 width and height, 558
 yield, 650
- Maxwell
 - Boltzmann velocity distribution, 407
 random variable, **669**
 James Clerk, 519
- Maxwell's equations, **624–625**, 630–631, 657
- McClellan
 transforms, 7, 327, **366–373**, 691, 713,
 718–721, 726, 732, 736
 James H., 368, 695, 718
- mean, 9, 14, 17, 48–49, 65–66, **152–153**,
 155–169, 171, 174–178, 186–189, 192,
 194–195, 199, 201–206, 211, 223–224,
 233, 288–289, 294, 303, 307, 316, 323,
 383, 385, 402–403, 439, 456, 474, 499,
 502–503, 506, 517–518, 537, 543, 556,
 620, 622, 665–673, 675–677, 686, 708,
 712, 727
 square, 17, 48–49, 65–66, 223–224, 233, 499,
 502–503, 506, 517–518, 537, 543, 556,
 686, 708, 712, 727
 square convergence, 49, 65–66, 223–224, 233
 square error, 233, 517, 537, 543, 556, 708
- measure theory, vi. Also see – Lesbegue
 measurable, 104, 502
- median, 155
- Mellin
 convolution, **134**, 602–603
 transfer function, **134**, 141
 transform, xiv, **134**, 141, 226, **603**, 715
- memoryless systems, **107–111**, 133, 135, 142
- mercury thermometer, 4
- Mersenne
 numbers, 9, 662, 723
 primes, 662, 702
- Meyer, Michael G., viii, 721
- Michelson
 Albert Abraham, 17
 - Morley experiment, 17
- middle C, 411, 614, 637
- Middleton, D., 218, 373, 719, 724
- mild conditions, 186. Also see – loose
 conditions
- million dollars, 8, 656, 658
- minimum
 mean square error, 537, 556
 negativity constraint, 493, **516**, 691, 704–705
 norm, 506
 sampling density, 387, **392–395**
 sampling rate, 217, 222, 277, 408, 720.
 Also see – Nyquist rate & minimum
 sampling density
- Minkowski
 addition, xi, **571–572**, 579, 590, 596
 algebra, **576**
 arithmetic, **570**, 575
 subtraction, xi, **573**
 operations, 57
 sum, 571–572, 590–591
- minor
 chord, 620–621
 key, **620–621**
 seventh, 615
 scale, 656
 third, 616
- mixed random variable, **203**, 211
- Miyamoto, Robert T., viii, 716
- mode, **155**, 616, 618, 705, 740
- modified Bessel functions, xii, 39–40, **64**,
 92–93, 202, 415
- modulated
 input, **418**
 signal, 124–125, 133, 216
 window, **423**, 441
- modulating sinusoid, 8
- modulation, ix, 6, 8, 15, 21, 51, 67, 68, 122–125,
 133–134, 204, 216, 268, 276, 331, 357,
 558, 613, 644, 683–684, 699, 717, 738, 740
- profiles, 558
- theorem, 21, 357, 644, 684, 738

- Modulo Man image, 138, 147
moment, xiv, 9, **152**, 154–156, 165, 167–169, 196–197, 200–210, 665–666, 671–672, 683, 694, 696, 699, 705, 713
momentum, 645–646
Monge, Gaspard, 5
Monika image, 137
morphology, vii, 7, **570**, 703
mortgage, 8, 647, **655–656**
motion blur, 8, **137–138**, 146
movie, 4, 32, 326
moving target, 441, 734
multidimensional
 Abel transform, 348
 area, 354
 comb lemma, **356–357**, 373
 convolution, 7, **332–333**
 cosine transform, 327
 differential, xii
 Dirac delta, **356**
 discrete Fourier transform, **359–360**
 Fourier analysis, 4, **330**, 357
 Fourier series, 331, 334, 336, 341, **356**
 Fourier transform, **352**, 399, 425, 726
 function, 327, 341, **360**. Also see –
 multidimensional signal
 parallelogram, 353
 periodic function, 348
 periodicity, 352, **354**
 sampling, 374–375, 402, 716
 sampling theory, vii, 352, **373**, 375, 381, 699, 729
 scaling, 337
 signals, vii, 6–7, 10, 326–328, 359, 368, 695, 712, 717, 719, 729–731, 740, 743.
 Also see – multidimensional function
 signal analysis, **326**
 symmetry, 6
 system, **404**, 712, 717, 743
 tiles, 380
 time scale, 604
multiplex, 122, 133, 411–412
music, vii, 4, 6–8, 414, 424, 610, 612–614, 616, 618, 656, 658
musical
 notation, xi
 musical score, 4, 7
- N**
- Namias, V., 126, 718, 720
Napier, John, 519
Napoleon, 5–6
Napoleon's Egypt invasion, 6
natural numbers, xiii, 584
narrow
 frequency band, 417
 window, 418. Also see short duration
 window
 negative binomial random variable, 175, 190, **202–203**
Nelson, Alan C., viii, 721
neural networks, 495, 691, 716, 721, 730
neurophysiology, 424, 484
Newton, Isaac, v
Newtonian physics, 613
Newton's second law, 611
NINV, **294–296**, 298–302, 307–311, 318, 322–325, 403, 459, 461–463
noise level, 179, 185, 194, 197–198, 243, 261, 265, 289–292, 295, 301, 303, 306, 308–310, 312, 322, 324, 384–386, 402, 457–458, 461–463, 482, 520, 529–530, 727, 736
NMR, see nuclear magnetic resonance
nonanticipatory system, 107. Also see – causal
 signal
noncentral
 chi-squared random variable, **667–668**, 673
 F random variable, **673**, 675
 Student's t variable, **676**
nondestructive testing, 424, 434, 723
nonexpansive, 559, 563, 722
 function, **559**, 567
 operator, **558–559**
nonstationary, 436, 690, 699, 708–709, 712, 714, 744
nonuniform sampling, 242, 257, 272, 277, 688, 690–691, 694, 698, 701, 714, 717–719, 725–726, 730, 734, 736–737, 739, 742
norm, xi, 327–328, 404, 486, 506, 510–511, 681, 689, 740
 of a sequence, 501
normal
 random variable, **160**, 667–670, 673
 tissue, 557
normalized, 178, 188, 237, 305, 369, 415, 557, 560–561, 645
 error, 309
 frequencies, 615
 harmonics, 615, 618–620
 interpolation noise, 294–296, 385, 463
 lower bound, 310
 pixels, 517
 probability density function, 163
 random variable, 186
 window, 420
notation table – see tables
notch filter, **121**, 711
nuclear magnetic resonance, 3, 720
null space, xi, **503**, 506, 510–511, 515
Nyquist
 density, 9, 247, 327, **376–382**, 385–387, 390, 392–396, 402, 691, 716. Also see –
 minimum sampling density
 interval, 252, 257, 259, 303
 Harry, 218, 721

Nyquist (*cont'd*)

rate, 8, 218–219, **222**, 226, 232, 234–235, 237, 250–252, 258, 260, 269, 275–276, 283, 291, 294, 298–299, 302–303, 306, 323, 376, 381, 396, 402, 461, 475, 698, 711. Also see – minimum sampling rate

O

octave, 411, 414, **613–623**, 656–658

odd

component, 13, 21, 24, 29, 65
 function, xiii, **13**, 32, 45, 63, 65, 78, 81–83, 86, 88, 96, 166. Also see – odd signal
 integrand, 83, 167, 460
 index, 33
 moments, 207
 signal, **12–13**, 563, 567. Also see – odd function
 summand, 283
 term, 13

offset

matrix, **389**
 vectors, **388–389**, 510–511

Oh, Seho, viii, 426, 433–435, 500, 537, 551–554, 557, 559–562, 692, 712, 716, 721

ohm, 11, 196–197

opening, xi, 574, 581, 595, 608
 duality, **581**

operator norm, 486

optical image, 385, 393, 690–691, 701, 713, 736, 738

optics, vii, 3–4, 112, 126, 333, 415, 447, 624, 626, 628, 631, 639, 641, 642, 644, 657, 683–684, 693, 697, 700–701, 710–712, 722, 733–734, 737–738

optimal

detection theory, 203
 periodic replication, 378

optimization, 495, 686, 692, 713, 721, 734–735

orthant, 504, 510, 517

orthogonal, 9, 40–41, 43, 48, 50, 69–70, 89, 95–96, 150, 273, 362–363, 383, 414, 473–475, 484, 502–503, 506, 510, 517, 688, 694, 706–707, 712, 721, 724, 732, 742. Also see – orthonormal

basis, 9, **48**, 50, 150, 273, 362–363, 383.

Also see – orthonormal basis

complement, 506
 functions, 473, 475
 polynomials, **40**, **50**, 694, 706

orthonormal, **48–50**, 274, 278, 474, 523

basis, **48–49**, 274, 278. Also see – orthogonal basis

oscillators, 124, 134, 419, 706

oscillator frequency, 134

oscillatory, 41, 233

output noise level, 308–309, 457, 461

outside boundary, 576

oversample, 8, 243–245, 247, 261, 275, 277–278, 285, 286–287, 535, 550, 697, 703, 715, 731

overshoot, 9, 16, 70, 100

oxymoron, 168

P

Page distribution, 431, 723

Papoulis'

generalization, 6, 242, **252**, 256, 261, 302, 394, 691
 proof, 223

Papoulis

Athanasios, vi–vii, x, 218, 252, 477, 642, 690, 699, 704, 723, 729, 741
 - Gerchberg algorithm, 477, 514, 516, 690, 697, 716, 726, 735, 741. Also see – PGA

parabolic

approximation, 639
 conic section, 634
 impulse response, 634
 wave, 635

parallel

connection, 422
 lines, 608
 planes, 567
 sides, 408
 slices, 397–398
 subspace, 513

parallelogram, 336, 353–354, 376, 393–394, 403, 405, 408

periodicity, 403
 subtile, 393–394
 tile, 355, 394

parameter estimation, 424

paraxial approximation, 639

Pareto

random variable, 187, **665–666**
 Vilfredo Federigo Samaso, 518

Paris, 4–6

Park, Dong Chul, viii, 534–543, 723

Park, Jiho, viii, 527–528, 532, 534–543, 723

Parseval's theorem, **16**, **47–49**, 88, 101, 190, 200, 231, 303, 320, 324, **485**, 645, 714, 718, 722

Parzen window, 187, 402, 407, 415, 419–420, 724

Pascal's

triangle, 662
 wager, v–vi, 151

Pascal

distribution, 154
 random variable, 202
 Blaise, 151, 288, 519, 570, 724

Pask, C., 449, 724

pattern recognition, 126, 495, 683, 743–744
 peak signal-to-noise ratio, x, 366, 532.

Also see – PSNR

- Pearson III random variable, 153, 175, 190, 202, 210–211
- pellicle, 643
- pencil beam, 546–547
- perfect
 - fifth, 614–615, 622
 - fourth, 613–614, 622
- periodic, 9, 11, 14–17, 21, 31–32, 47, 51, 53–55, 67, 70, 91–93, 118–119, 127, 136, 139, 149–150, 197, 218, 222–223, 227, 238, 243, 266, 303, 327, 342, 344, 352–358, 354–357, 358, 402, 448–450, 455, 457, 453–454, 462–463, 465, 469–470, 472, 484, 448–450, 483, 486, 490, 605, 643, 647, 652, 684–685, 694, 705, 716–718, 730, 734
- bandlimited functions, 218, 266
- continuous sampling, **448–450**, 462–463, 483
- decimation, 465, **387**
- deposits, 647, **652**
- function, xiii–xiv, 9, 14–17, 31, 47, 51, 54–55, 67, 91, 93, 218, 222–223, 342, 352, 356–357, 402, 455, 457, 469–470, 472, 484, 486, 490, 643, 684–685, 734. Also see
 - periodic signal
- nonuniform decimation, **463**, 465, 470
- replication, 55, 327, 354–356, 358, 378, 604
- sequence, 54, 490
- signal, **11**, 21, 54, 70, 119, 150, 327, 686. Also see
 - periodic function
- spectrum, 467
- string, 54
- trigonometric polynomial, 644
- periodicity, 32, 126, 352–354, 356–359, 373–374, 376–379, 389, 391, 403, 467, 484, 489, 604, 647, 720, 735
- cell, 358, 403
- matrix, **353–354**, 356–357, 359, 373–374, 376–379, 389, 391, 604
- subtile, 389, 392
- vector, **352–355**, 376–377
- periodically
 - sampled, 448, 719, 725
 - spaced, 448
- Peterson, A., 587, 680, 685, 719
- Peterson, D.P., 195, 330, 335, 625, 719
- PGA, **477–482**, 485–487, 515–517, 642–643. Also see
 - Papoulis-Gerchberg algorithm
- phase, vi, 46, 115–117, 120, 123–124, 133, 219, 275, 327, 360–361, 366–367, 416, 495, 511–512, 566, 568, 628, 630, 634, 636, 639, 681, 690–692, 695, 698–700, 702–703, 710, 715, 720, 722, 726, 737–741
- arbitrary – see arbitrary phase
- carrier frequency – see carrier frequency phase
- conjugation, **657**, 659
- constant – see constant phase
- delay, 639
- images, 360
- in image characterization, **360**
- of a complex exponential, 419
- of a DFT, 360
- of a Fourier transform, 8, 360–361
- of the frequency response, 120
- plots, 569
- pure – see pure phase
- quadratic – see quadratic phase
- sampling, 219
- shift, 116–117. Also see
 - shifting phase
- synthesized – see synthesized phase term, 639
- zero – see zero phase
- phased array, 643–644, 684, 686, 703, 714
- Philipp, Harald (Hal), viii
- PI, ix. Also see pseudo inverse
- PIA, ix, 131. Also see
 - piecewise invariant approximation
- piano, 613
- piecewise
 - constant integration, 226
 - invariant approximation, 130–133, 136, 143, 150
 - linear approximation, 226
 - linear interpolation, 226, **249**
 - linear signal, 277
- pin hole, 630
- pipe organs, 613
- pitch, roll and yaw, **399**
- Pitton, James W., viii, 721, 725
- pixel, 179, 360, 362, 364, 366, 517–519, 527–530, 532–534, 538–539, 541–542, 544, 546–547, 566, 569, 578–579
- aperture, 533
- array, 547
- block loss, 534, 541
- Planck's
 - constant, xii, 198, 645
 - radiation random variable, 665, **677–678**
- Plato, 447
- POCS, x, 7, 327, 438, 447, 482, **495–496**, 498–501, 514, 516–518, 520–522, 525–527, 529–533, 535, 537, 539–546, 550–553, 556–566, 568, 680–681, 692, 699, 703, 705, 709, 711, 713, 716, 722–723, 728, 733–734, 736–739, 741–742, 744. Also see
 - alternating projections onto convex sets
- associate memory, **517–518**, 520–522, 525–526
- convergence, 499–500, 517, 530
- kernel, 553
- restoration, 529, 535, 539–541
- synthesis, 544
- point
 - masses, 152
 - spread function, 112, 330, 333, 404, 631–632
- pointwise convergence, 66, 694

- Poisson
 approximation, **177**, 193–194
 counting process, 194–195, 199, 204
 point process, **193–195**, 199
 random variable, **171–172**, 176, 190, 201, 204
 Siméon Denis, 518
 sum formula, **47**, 52, 89–90, 234, 236, 248,
 253, 267, 303, 308, 317, 688, 717
- polar
 coordinates, xi, 15, 46, 341–342, 344–345,
 350, 687, 717, 733, 741
 form, 46, 344
 Fourier series, 345
 representaion, **344**
- polarization, 624
 polarized, 527
- Pollak, H.O., 473, 711, 725, 731
- Pólya distribution, 154
- Polybius of Megalopolis, 413, 725
- polymers, 3, 705
- popcorn, 194
- power, xiii, 11, 47, 50, 76, 84, 89, 120, 124,
 142, 187, 192, 196–200, 204, 211,
 214–216, 231, 233, 263, 290–291, 308,
 324, 427, 460, 490, 685, 703, 723, 726,
 736–738, 742
- point presentation, viii
- spectral density, xiii, **196–200**, 204, 214–215,
 233, 290–291, 308, 324, 427, 460, 685,
 723, 738
- theorem, **47**, 50, 76, 89, 142, 231, 263,
 460, 490
- prediction, 447–449, 477, 624, 686–689,
 714–715, 720, 724, 732, 740
- prime
 numbers, 586, 596–599, 601, 662, 702
 ratio, 615–616
- probability, vi–vii, xii, xiv, 6, 10, **151–174**,
 177–179, 186–193, 201–203, 207–211,
 213, 314–316, 319, 401, 510, 564–566,
 568, 601–603, 645, 665–679, 693, 723,
 733, 735, 740
- density function, xii, xiv, **151–154**, 155,
 157–171, 173, 178–179, 187–190, 192,
 201–203, 206–207, 209–211, 213,
 314–316, 401, 510, 564, 568, 645,
 665–679, 693
- mass, **153–154**, 168–174, 177–178, 191,
 202–203, 568, 601–602
- mass function, 154, 170–172, 191–192, 203,
 601–602
- projection, vii, x, 7–8, 327, 345–359, 351–352,
 402, 406, 426, 433–435, 438, 495,
 497–502, 504–512, 514, 517, 522,
 527–562, 564, 566–567, 585–586,
 691–694, 697, 702–703, 706, 708, 710,
 712, 716, 721–724, 726, 729–731,
 733–735, 738–742, 744. Also see –
 tomographic projection
- matrix, **506**, 517, 522, 548
 operator, 497, 504–506, 541, 555–556, 559
- prolate spheroidal wave function, x, **48–49**, **473**,
 701, 709, 711, 727, 731. Also see – PSWF
- propagation, vii, xii, 4–5, 623–629, 657, 687,
 694–695, 705–706, 726–727, 729,
 736–737, 740–742
- direction, 628, 657
 of the angular spectrum, 629
 vector, xii, **626**
- prototype filter, **367**, 370–371, 402
- pseudo inverse, x, **506**, 547, 556
- PSNR, x, 366, 532. Also see – peak signal to
 noise ratio
- PSWF, x, **473–477**, 480, 484–485, 491.
 Also see – prolate spheroidal wave function
- coefficient, 475, 484
 expansion, 484
- pure
 phase, 639
 tone, 68
- Pythagoras, viii, 518, 613–614, 618
- Pythagorean
 harmony, **613–614**, 618
 scale, **657–658**
 theorem, **62**, 73–74, 627
- ## Q
- Q of a filter, 439
- quadratic
 equation, 85, 661
 formula, 76, **85**
 phase, 636, 659
- quadrature, 472, 686, 724
- quality factor, 439
- quantization, 7–8, 364–365, 535, 537, 550,
 688–689, 700, 709–710, 735
- error, 7–8, **535**, 537, 550
 level, 535, 537
 matrix, 364
 operator, 535
- quantum
 leap, 64
 level, 645
 mechanics, 126, 681, 709, 714, 720–721, 739
- quarter note, 411
- queuing theory, 160
- quotient rule, 156
- ## R
- radar, 3, 126, 424, 441, 681, 686, 691–692,
 695–696, 700, 706, 714, 729, 740
- Radbel, Dmitry, viii, 715, 726
- radiotherapy, 7–8, 495, **545–545**, 554, 557,
 559–562, 685, 712, 735
- Radon transform, 345, **349–352**, 402, 533
- Ramon, Ceon, viii, 721
- ramp response, **118**, 120

- random variable, vi–vii, xii–xiv, 6, 9, **151–179**,
 186–187, 189–190, 194–195, 201–207,
 209–211, 306, 314, 323, 401, 407,
 601–602, 664–679, 723
 Bernoulli – see Bernoulli random variable
 beta – see beta random variable
 binomial – see binomial random variable
 Cauchy – see Cauchy random variable
 chi – see chi random variable
 chi-squared – see chi-squared random
 variable
 deterministic – see deterministic random
 variable
 discrete uniform – see discrete uniform random
 variable
 Erlang – see Erlang random variable
 exponential – see exponential random
 variable
 extreme value – see extreme value random
 variable
 F – see F random variable
 Fisher-Tippett – see Fisher-Tippett random
 variable
 gamma – see gamma random variable
 Gaussian – see Gaussian random variable
 generalized Cauchy – see generalized Cauchy
 random variable
 generalized Gaussian – see generalized
 Gaussian random variable
 geometric – see geometric random variable
 Gumbel – see Gumbel random variable
 half Gaussian – see half Gaussian random
 variable
 half normal – see half normal random
 variable
 hyperbolic sechant – see hyperbolic sechant
 random variable
 independent – see independent random
 variable
 Laplace – see Laplace random variable
 log normal – see log normal random
 variable
 log-Weibull – see log-Weibull random
 variable
 logistic – see logistic random variable
 Maxwell – see Maxwell random variable
 mixed – see mixed random variable
 negative binomial – see negative binomial
 random variable
 noncentral chi-squared – see noncentral
 chi-squared random variable
 noncentral F – see noncentral F random
 variable
 noncentral Student's – see noncentral
 Student's t random variable
 normal – see normal random variable
 normalized – see normalized random
 variable
 Pareto – see Pareto random variable
 Pascal – see Pascal random variable
 Pearson III – see Pearson III random variable
 Planck's radiation – see Planck's radiation
 random variable
 Poisson – see Poisson random variable
 Rayleigh – see Rayleigh random variable
 Rice – see Rice random variable
 sechant – see hyperbolic sechant random
 variable
 triangle – see triangle random variable
 uniform – see uniform random variable
 uniform difference – see uniform difference
 random variable
 uniform product – see uniform product
 random variable
 uniform quotient – see uniform quotient
 random variable
 uniform ratio – see uniform ratio random
 variable
 Von Mises – see Von Mises random variable
 Weibull – see Weibull random variable
 raster, 7, 395–397, 403, 408, 683
 sampling, 7, **395–397**, 403, 408
 scan, 395, 397
 rational
 numbers, 17, 424, 601, 605, 692
 time scales, **600**
 ray
 of light, 639
 optics, 624
 tracing, 624
 Rayleigh
 random variable, **667–669**, 677
 - Sommerfeld diffraction, 624, 626–627,
 630, 633–635
 Rayleigh's theorem, 47
 real
 roots, 661
 signals, 15, **45**, 133, 196, 235, 436, **438**, 482,
 489, 512, 564
 time filters, 107
 time implementation, 440
 rectangle
 function, xiii, 14, 21, 23, **28**, 187, 588
 integration, 226, 228
 support, 377
 recurrent nonuniform sampling, 242, **257**,
 272, 277
 regularize, 482, 680, 682, 684, 729
 relatively prime, 597–599, 601
 relativity, 17
 relaxed
 constraint, 429, 539
 interference projection, **541**
 interpolation formula, 222, **247–248**
 nonexpansive operator, 559
 relaxation, 558
 reliability, 160, **201–202**, 208–209, 666
 remote sensing, 3, 495, 683, 708, 728

- Rényi, Alfréd, 217, 737
 repunit numbers, 9, 662, 702
 residue, 598–599
 arithmetic, 598
 number theory, 598, 732
 resistor, 11, 106, 116, 196–197
 resonant frequency, 215, 439
 restoration noise level, 384–386, 457–459, 463, 482
 Revelry, 616
 reverse integration, 19
 Rice random variable, **677**, 727
 Riemann
 integral, 104
 Georg Friedrich Bernhard, 519
 right dense, 587, 592, 608
 ringing Laplace autocorrelation, **198**
 robotics, 495, 709
 roll, 151, 169, 177, 399, 602
 roll-off, 248, 381
 Roman empire, 413
 Romans, v
 root, 45, 235, 239–240, 304, 439, 613–620, 622, 624, 630, 661, 667–668
 Ross, Hugh, 326, 628
 rotate, 118, 208, 337–341, 349–350, 380, 399–401, 559, 561–562, 565–566, 712, 741. Also see – rotation rotated
 gantry, 559, 561–562
 image, 401
 rotating wagon wheel, 4
 rotation, 6, 331, **336–341**, 349, 357, 378, 399, 404, 735. Also see – rotate
 and scale theorem, 357
 angle, 340
 in higher dimensions, 339
 in three dimensions, 339
 matrix, 337–339, 399
 rounded, 364–365, 535
 rounding, 658
 round off error, 478, 713, 720
- S**
- Sad Man image, 568–569
 Saint Augustine, 411, 681
 Saint Benoît-sur-Loire, 5
 Saint Joseph, 5
 sample
 and hold, **249**, 252, 717–718
 dependency, 243, 327, 716
 mean, **176**
 sampled DTFT, 53
 sampling
 density, 9, 235, 277, 327, 376, 379, 385, 387–395, 402, 691
 density comparisons, **379**
 matrix, **376–379**, 382, 387–388, 402
 phase, 219
 rate, xiii, 217, 222, 232, 239, 243, 270, 272, 277–278, 289, 291, 298–299, 301, 309–310, 322, 325, 392, 395, 408, 451, 692, 698, 703, 708, 716, 720
 rate parameter, xiii, **243**, 272, 278, 289, 301, 325
 theorem, vi–vii, 4, 6–7, 9, 15, 49–50, 202, 217–223, 227, 231, 234, 236, 242, 252, 256–257, 265, 267, 271, 273, 277–278, 293, 302, 304–306, 310–311, 313, 372–373, 375, 381, 448–449, 462, 474, 495, 680–716, 718–727, 729–741, 743–744
 theorem for periodic bandlimited signals, **218**
 theorem for signal-derivative sampling, **304**
 theorem tables – see tables
 theory for bandpass functions, **267**
 Sarr, Dennis, viii, 721
 savings accrual, 8, 647
 scalar
 diffraction, 627, 722
 optics, **624–625**
 time scale, 604
 scaling, 15, 20–21, 117, 156, 161 192, 336–338, 340–341, 399–400, 416, 721
 matrix, 337, 340, 399
 property, 21
 theorem, **20**, 156, 161 192, 406, 416
 science, 3, 10, 447, 570, 610, 646, 711, 731
 Schrödinger's equation, 192, 645
 Schwarz's inequality, 71, 73, 103, 224, 321, 440, **660–661**
 sech, 23–27, 66, 86, 132, 140, 153, 161–162
 cosech, 23
 sechant random variable – see hyperbolic sechant random variable
 second
 characteristic function, xiii, **155–156**, 160–162, 164, 166, 171, 174, 177, 205–206, 210
 derivative function, 156
 moment, 165, 168–169, 196–197, **200**, 204, 666, 571
 order aliasing, 254, 451, 479, 471
 order decimation, 403
 order miracle, 10
 order statistics, **193–194**, 29
 segmentation, 3, 738
 semitones, 411, 613–616
 separability, 6, 331, **334–336**, 395, 401.
 Also see – separable
 theorem, 334–335, 357, 395, 406
 separable, 157, 334–335, 401, 721. Also see – separability
 function, **334–335**, 401
 set
 subtraction, 576
 translation, 571
 Sezan, M. Ibrahim, 495, 697, 722, 730

- Shannon
 Claude E., viii, 217–220, 252, 259, 302, 730
 number, 232, 236, 475, 682, 706
 sampling theorem, xi, vii, 6–7, 217–218, 373, 683, 685, 686–689, 695, 697, 701, 703–707, 710, 716, 726, 732, 737, 743
 Shannon's proof, 221, 234
 Shepp-Logan phantom, 350
 shift
 invariant system, **106**, 230, 333, 630–631, 691. Also see – time invariant
 theorem, **15**, 19, 58, 100, 142, 145, 208, 210, 212, **332–333**, 341, 647
 shifting phase, 630
 short
 duration window, 418. Also see narrow window
 time Fourier transform, 126, **413–419**, 422–423, 435–436, 438–441
 shot noise, **199**
 sideband, 133
 sifting property, **19–20**, 31, 33, 84, 112–113, 128, 443, 626–627, 640
 signal
 detection, 424, 708, 712, 737
 integral property, **45**, 77, 87, 200
 level, **194**
 norm, xi, 503
 of samples, **51**, 243, 25
 processing, vii, ix, 3, 10, 52, 424, 434, 496, 722, 729–730
 recovery, vii, 7, 126, **447**, 610, 693, 695, 717, 724, 495
 synthesis, 126, 438, 700, 726, 739
 -to-noise ratio, x, 366, 475, 532
 signum function, xiii, **29**. Also see – sgn
 sgn, xiii, 14, 17, 22–23, 29–30, 46, 63, 65–66, 77, 83, 101, 140, 166, 230, 239, 275, 278, 280, 351, 370, 441. Also see – signum function
 simultaneous
 equations, 7, 253, 256, 258, 330, **514**, 532, 563
 switching tone, 433, 435
 weighted projections, **500–502**, 514
 simultaneously
 sample, 9, 242, 260, 303
 sounded harmonics, 612–613
 sinc function, 14–15, 17, 21–22, **27–28**, 32–33, 35, 37, 39, 49, 63–67, 70, 76–78, 86–93, 97–98, 101, 107–109, 121–122, 129, 132–133, 137, 139, 141, 150, 153, 159, 219–220, 222–225, 227–234, 236–239, 242–243, 245–247, 249, 251, 253, 258–263, 266–267, 269, 271–274, 277–286, 289–291, 293–298, 301–302, 306–307, 310–311, 314, 319–320, 324, 335–336, 340–341, 357–358, 370–371, 392, 408–410
 sin, xii, 17, 21–22, 24, 27, 29, 32–33, 39, 57–58, 63, 66, 69, 77–78, 81–82, 84, 87, 90, 93, 96–100, 124, 218, 220, 228–230, 232, 238, 262–263, 267, 270, 273, 278, 280, 284, 306, 311, 320, 337, 339, 341–342, 350–352, 371, 402, 404, 412, 455, 488–489, 611–612, 663. Also see – sine transform, 65. Also see – sine transform
 sine, xiii, xiv, 24, 57, 61, 62, 262, 306, 420
 integral, xiii, **39**, 70, 87, 262, 306
 transform, xiv, 57, 717. Also see – sin transform
 wave, 420, 717
 single side band suppressed carrier, 119, 599.
 Also see – SSSC
 sinh, **24–26**, 86, 162, 203, 211–212, 291–292, 311, 324. Also see – hyperbolic sin
 sinogram, 402
 sinusoid, 3, 6, 31, 116, 125, 276, 412, 417–421, 429, 432, 441, 558–589, 682, 709, 721, 743
 slab, 508, 567
 Slepian's paradox, 482, 486
 Slepian, David, 10, 473, 482, 486–487, 731
 sliding window, 413, 416, 683, 716
 Fourier transform, 416
 slower roll-off, 381
 Smith, David Eugene, 447
 Smith, David K., viii, 715–716
 Smith, Michael J., viii
 sonar, 4, 126, 424, 434, 441, 624, 692, 700, 713
 spectra, 3, 52, 71, 222, 224, 232, 237, 240, 247, 253, 258–259, 270, 304, 377, 380–381, 385, 387, 394, 396, 402–403, 451, 453, 467–468, 472, 685, 698, 704, 706, 716, 718, 723, 725, 727, 736, 740. Also see – spectrum
 spectral support, 376–377, 379–381, 392–393, 395–398
 spectrogram, 4, 7, 415–420, 424, **431–436**, 439–440, 537, 551–553, 683
 spectrometry, 3, 683, 694, 716
 spectroscopy, 3, 690, 693, 698, 702, 706, 708–709, 729, 732, 737, 739–740
 spectrum, 4, 12, 21, 45–46, 51–54, 68, 72, 102, 122–124, 133–134, 197, 219, 222, 232, 234–235, 237, 239, 243, 248, 253–254, 258, 268, 270, 345, 374, 376–377, 380–381, 385–387, 390–391, 396–397, 402, 411, 416, 418–419, 450–452, 456, 467, 472, 477, 483, 489, 516, 626–630, 657, 683, 705, 714, 717, 738. Also see – spectra
 speech, 126, 424, 434, 436, 495, 691, 702, 712, 715, 717, 722, 728, 733, 738, 744
 spherical
 Bessel functions, xii, 9, **39**, 41, 61, 69, 89, 95–96, 133, 141, 263, 401
 harmonic, 345
 spherically symmetric, 341, 343, 401, 631

- spinal cord, 545
- square
- aperture, 532, 544
 - area, 73
 - diamond, 388–389, 391–392
 - doughnut, **392–393**
 - matrices, 405
 - root, 235, 239–240, 630, 667–668
 - subtiles, 395
 - summable, 265
 - tile, 395, 643
 - wave, 17, 64, 77, 100
- SSSC, x, 133. Also see – single side band suppressed carrier
- stable, 59, 107, 109–112, 135, 142, 726
- systems, **107**, 420, 441
- standard deviation, **155–156**, 177, 204, 318, 619, 621, 645, 518
- Stark, Henry, 495, 568, 724, 727, 730, 733, 742–743
- stationarity, 289. Also see stationary
- stationary, **195–199**, 204, 214, 233, 288, 293, 303, 307, 316, 323, 336, 385, 402, 416, 456, 684, 686, 690, 702, 710, 713–714, 719, 720, 725, 728, 732, 739
- in the wide sense, 195–197, 199, 204, 214, 233, 288–289, 307, 316, 323, 402, 456, 713, 741
 - processes, **195–196**, 702, 714, 720, 725, 732
- step response, 120
- Stirling's formula, 63, 74
- stochastic
- bandlimited signal, **316**, 320
 - input, **198**
 - processes, vi–vii, xiii, 6, 10, **151**, **193–194**, 196–198, 200, 204, 214–215, 233, 289–290, 316, 323, 383, 682, 684, 712–714, 723–725, 730
 - representation, 180
 - resonance, 6–7, **178–180**, 182, 204, 215, 699, 716, 719, 727, 744
 - signal, 316–318
- strictly
- convex sets, 497
 - positive, 239–240, 277
- strong
- convergence, 501
 - law of large numbers, 177
- structural analysis, 3
- structuring element, 575, 577–579, 582, 584
- student's t, 664, 676–677
- sub-Nyquist sampling, **393**
- subharmonics, **620–622**
- submatrices, 522
- subpixel resolution, 7, **532–533**, 545
- subspace, **503–509**, 513–517, 520, 522, 531, 563, 691, 734, 738, 744
- subtiles, **388–395**
- sufficient condition, 17–18, 105, 136, 383, 430, 486
- super resolution, 447, 495, 680–681, 685, 695, 696, 698, 700–701, 705, 708, 714, 720, 724–725, 741
- superposition, 106, 113, 115, 127, 129–130, 135, 150, 335, 398, **434**, 635, 696
- integral, **113**, 115, 127, 129–130, 135, 398, 635
 - of plane waves, 626–627
 - of point sources, 626
 - of sinusoids, 6
 - of separable functions, 335
 - sum, **113**, 330, 398
- support, 150, 253, 268, 376–377, 379–381, 385–386, 391–398, 403, 432, 434, 570, 572–573, 575, 689
- domain, 570
- symmetric
- Fourier-Bessel transform, 345
 - function, **341–346**, 401, 406. Also see – symmetric signal
 - kernel, 430, 543, 551–552
 - Laplacian, 631
 - signal, **12**, 45, 70, 200, 235, 472, 483, 564. Also see – symmetric function
- symmetrically spaced, 334
- synthesize
- a diffraction grating, 643
 - beam, 547, 558–559
 - from images, 8
 - GTFR kernels, 426, 434
 - phase, 568–569
 - using POCS, 537, 539, 543, 551–552, 556
- system
- operator, xiii, 104, 110, 129, 142
 - theory, vi–vii, **104**, 139, 106, 404, 702, 708, 715
- ## T
- tables
- acronym, ix–x
 - convolution (c)
 - continuous time c algebra, 115
 - discrete time c algebra, 115
 - sampling theorem even and odd function properties, 13
 - extrema of sinc, 92
 - Fourier transforms (FT)
 - characteristic functions, 153–154
 - continuous FT theorems, 13
 - discrete FT theorems, 13
 - FT pairs, 22–23
 - FT types, 13
 - multidimensional FT properties, 331
 - GTFR's
 - kernel transforms, 425
 - special cases, 431
 - notation, xi–xiv
 - optical systems summary, 642

- probability functions (pf)
 continuous pf's, 1153
 discrete pf's 154
- sampling theory
 directly sampled, 272
 history, 218
 noise levels, 462
- windows
 commonly used, 415
 cosine transform relationships, 420
- tanh, 23–24, 26–27, 66, 86, 140, 162.
 Also see – hyperbolic tan
- taps, 616
- target
 border, 558
 detection, 126
 dose, 548–549
 organ, 560–561
 shape, 557–558
 volume, 548
- taxes, 647, 651–652, 654, 658
- Taylor series, xix, **12**, 22, 24, **61–62**, 73, 155,
 171, 186, 202, 208, 210, 259, 261,
 265–266, 311, 325, **448–449**, 486–487, 634
- arctan, 312
- cardinal series, 265–266
- characteristic function, 155
- confluent hypergeometric series, 210
- cosine, 24
- exponential, 22
- Gaussian, 208
- log, 61
- sine, 24
- truncated, 634
- Taylor, Brook, 519
- Tchebycheff – see Chebyshev
- television, 4, 395, 495
- tempered scale, 7, 610, **613–623**, 657–658
- template matching, **517**
- TFR, x, **411–413**, 419, 427. Also see – GTFR
- thermal
 equilibrium, 669, 739
 noise, **197–198**
 resistors, 106
- thermometer, 4
- thesaurus, 196
- thin lens approximation, **639**
- Thompson, Benjamin B., viii, 716
- Thomson, William – see Kelvin, Lord
- Three Dolls, 576
- threshold, 179–180, 475, 681, 743
 detector, 178, 716
 image, 180, 185
- tic tac toe, 328–330, 299, 404
- tighter integration, 381–381
- tile, 354–359, 373–374, 376–381, 383–395,
 643. Also see – subtitle
- time-
 - bandwidth product, 218, **231–232**, 473, 475
 - frequency distribution, 417, 433–435, 537,
 551–553, 692, 696, 702, 705, 709,
 712–713, 721–723, 727, 738, 741, 744.
 Also see – time-frequency representation
 - frequency representations, vii, ix–x, 4, 7,
 126, 327, **411**, 417, 424, 436, 537, 680,
 689, 691–693, 708, 720–721, 725, 741,
 744. Also see – TFR & time-frequency
 distribution
 invariant, x, 6, **106**, 108–112, **114**, 130,
 133, 135–137, 142–144 196, 333, 439.
 Also see – shift invariant
 marginal, **427–428**
 resolution, **416–418**, 428, 436, 439, 537–539,
 541–542
 resolution constraint, **428**, 539, 541
 resolution versus frequency resolution trade
 off, **416–418**, 436, 439
 scale, vii, ix, xi, xiii, 7–8, 326, 328, **570**,
 583–592, 594–605, 608, 680, 685, 696,
 702–703, 714, 716, 726, 728, 734, 744
 series, 3, 685, 725, 733, 739
 time variant systems, **106**, 112, 130–131, 136,
 139, 698, 708
- Toeplitz, 452, 702
- tomographic
 projection, 7, 327, **345**, 348–349, 406,
533, 548
 reconstruction, 546, 565
- tomography, ix, 3, 7, 327, **345**, 352, 424, 495,
 546, 683, 708, 711, 715, 728, 730, 733, 741
- tonal color, 613
- transcendental
 equation, 563, 567
 function, 6, 697, 721
 relationship, 202
- transfer
 function, 60, 134, 248, 308, 421, 423, 440,
 442, 682, 708, 725, 735
 kernel, 127, 226–227
- transfinite numbers, xii, **139**, 150, 689
- transformation function, **367–371**, 373, 402
- translation, 218, **404**, 510, 571, 574, 683, 695,
 704, 709–710, 739, 743
- transpose, 15, 51, 117, 235, 347
- theorem, 347
- transposition, 127, 327, 331, 333, **336–338**,
 340, 399
- trapezoidal integration, **225–228**, 230
- triangle
 function, xiii, **32**, 64, 458
 random variable, **159**
- trigonometric
 function, **21**, 24, 220
 geometric series, 169, **663**
 polynomials, **266**, 272, 276, 322, 453, 456,
 469, 483, 644
- tritone, 621–622

trombone, 613
 truncated
 cardinal series, 223, 225, 233, 320
 IIR filters, **419–420**, 422–423
 Fourier series, 16–17, 70, 98, 107, 224
 Foutier transform, 642
 PSWF, 474
 signal, 475
 sinusoid response, 420–421
 Taylor series, 634
 truncation error, 232, 245, 248, **320–321**, 323,
 684, 686, 688–689, 696, 703, 706–709,
 714, 725, 735, 742
 Tseng, Shiao-Min, viii, 300, 716, 736
 tuba, 234
 tumor, 545–546, 554, 557, 560–561
 twelfth root of two, 613

U

ultrasound, 126, 424, 434, 684, 716, 721
 unbiased
 estimate, 314–315, 318–319
 interpolation, **314**, 316
 restoration, **318**
 unbounded, 319
 AITS, 596
 degree of aliasing, 462
 Dirac delta, 110
 energy, 304
 from above, 569
 from below, 569
 variance, 306
 uncertainty
 principle, vii, 7–8, 192, 416, **645–646**, 657,
 704, 710
 relationship, 192, 202, 645–646
 unfiltered
 interpolation formula, 291
 NINV, 298–301, 323
 restoration, 295, 298
 uniform, 9, 17, 49, 53, 56, 137, 153–154,
 159, 164, 169–170, 175, 177–179,
 187, 204, 214, 219, 223–225, 231, 232,
 304, 319, 376, 385, 461–462, 474, 533,
 558, 610, 671–672, 686, 689, 702,
 706, 738
 convergence, 49, 223–225
 difference random variable, 159
 jitter, **319**
 motion blur, 137
 probability density function, 671
 product random variable, **671–672**
 ratio, 9, **159**, 164, 169–170, 177–179, 187,
 323, 671–672
 quotient random variable, 671
 random variable, 9, **159**, 164, 169–170,
 177–179, 187, 323, 671–672
 ratio random variable, 672

unilateral
 cosine transform, **56**, 65
 Laplace transform, 18, 228
 unit
 area, 20–21, 23, 156, 188, 354, 376, 564
 circle, 58, 343, 694
 delay, 59
 doublet, 205
 energy, 48, 485, 491
 norm, 510, 511
 periodicity, 368
 gain, 422
 graininess, 598
 interval, 50–51, 188, 205, 403, 405
 length, 628
 multiply, 59
 norm, 510–511
 period, 50, 368
 radius, 328, 343, 408, 410
 slope, 408
 square, 370, 398
 step, xiii, 14, **30**, 58, 65, 111, 120, 133, 140,
 228, 346, 419, 430, 586
 variance, 162, 167, 187, 667, 676
 vector, 510–511, 514, 627, 631
 unitless, 12, 50
 units, 12, 14, 60, 200–201, 204, 312, 328, 354,
 398, 423, 439–440, 634
 universal
 agreement, 614
 set, 497
 upper
 integration limit, 488
 bound, 512, 686, 708, 719, 722, 734
 case letter, 450
 envelope, 124–125
 frequency, 267
 limit, 439, 554
 sideband, 133, 268
 upsampling, **236**
 unstable, 107, 247, 259, 303, 319, 383, 449

V

Vandermonde determinant, 257, 275, 286
 variance, xiii, 153, **155–160**, 162, 164, 166,
 167–172, 174–178, 187–189, 192, 194,
 201–206, 211, 292–294, 296, 302–304,
 306–307, 313, 315–316, 323, 384,
 402–403, 463, 665–673, 675–677, 679
 Vatican, 139
 vectorization, **329**
 vector
 arbitrary – see arbitrary vector
 beam – see beam vector
 column, 37, 532. Also – see long column
 vector
 component, 521, 605, 628, 664
 curl, xi, 332
 displacement – see displacement vector

- dose – see dose vector
eigen – see eigenvector
elements, 605
identity, 229, 625
image – see image vector
library – see library vector
matrix – see matrix-vector
maximum – see maximum vector
norm, xi, 327
offset, 517
operator, 229, 625
optics, 624
periodicity – see periodicity vector
propagation – see propagation vector
offset – see offset vector
response – see response vector
stimulus, 527
subtile – see subtile vector
unit – see unit vector
weighted – see weighted vector
velocity
 measurement, 3, 734
 sampling, 9
Venn, John, 518
vertical, 398, 411–412, 528
 bars, 4
 displacement, 611
 force, 610
 line, 348, 515
 scale, 454–455
 slice, 395, 397–398
 swath, 418
vibrating
 air column, 613, 616–617
 lips, 616, 618
 string, 610–613, 617–618, 656–656
vibration
 analysis, 424, 434, 713, 744
 mode, 616–617
vibrational harmonics, 623
video
 disc, 495
 processing, 495
viola, 613
violin, 613
volt, 60, 197, 201, 204
voltage, 11, 84, 116, 151, 196, 439
Von Mises random variable, 202, **670–671**
Von Neumann's alternating projection theorem, **514**
Von Neumann, Johann, 242, 721
- W**
- Walkup, John F., viii, 445 702, 708, 715, 738
Walsh function, 50, 278, 708
Wang, Y., 739
watermarking, 495, 681
WAV file, 107
- wave
 equations, vii, **190, 610–614**, 617, **624, 626–627**, 656–657
 function, x, 48–49, 190, 192, 473, 645–646, 711, 727, 731
 packet, 645, 726, 412
 propagation, vii, 4, **623–624**, 628–629, 657, 695
 waveform, 4, 84, 249, 412, 475, 699–700
 wavefront, 627, 634, 657, 659, 733–734
 wavelength, xiii, 623, 625–626, 628, 630, 633–634, 637, 645–646, 685, 690
 wavelets, xiii, 9, 626, 683, 686, 692–694, 698, 701, 707, 711, 719, 730, 734, 736, 738–739, 741, 744
 weak
 convergence, 501, 722
 law of large numbers, 6, 158, 177–178, 501, 722
 weather analysis, 3, 698
 Webb, H., 495, 733, 742
 Weibull random variable, **665–668**, 675
 weighted
 area, **510–511**
 Dirac delta, 21
 distance, 501
 fractional Fourier transform, **128–129**, 138–139, 148–150
 function, 511. Also see – weighted signal
 Hermite polynomial, 43
 sum, 468, 501–502, 508
 noise level, 149
 probability, 568
 projection, 501–502
 signal, 510. Also see – weighted function
 vector, 510
 weights, 128–129, 138, 149, 451, 453, 501–502, 556, 627–628, 644
 Weil, Andre, 411
 Welch window, 415, 693
 well-posed, 306, 463, 476–477, 484–485, 491, 493
 western harmony, 8, **613**
 western
 movies, 4
 music, vii, 7–8, **610**, 612–614, 623, 656
 tempered scale, 615
 white
 Gaussian noise, 518, 699
 noise, 9, **197–198**, 290, 292–295, 302–303, 309–310, 312, 323–324, 385, 402, 457, 459–460, 463–464, 518, 527, 533, 569, 699
 Whited, John L., viii, 715
 Whittaker, Edmund Taylor, 218–219, 739
 Whittaker, J.M., 218–219, 739
 Whittaker-Kotelnikov-Shannon sampling theorem, 217, 683, 689, 697, 705
 Whittaker-Kotelnikov-Shannon-Kramer sampling theorem, 217

- Whittaker-Shannon sampling theorem, 217, 687–688, 726
- wide
- sense cyclostationary, **323**
 - sense stationary, 195–197, 199, 204, 214, 233, 288–289, 307, 316, 323, 402, 457, 713
 - window, 418. Also see – long windows
- Wigner distribution, 431, 434–435, 537, 551–553, 682–683, 687, 692, 700, 706, 720, 726, 735, 739
- windows, 56–57, 187, 402, 407, 413–420, 422–424, 431–432, 434–436, 438, 441, 490, 544, 644, 681, 683, 696, 716, 722, 740
- Blackman – see Blackman window
 - boxcar – see boxcar window
 - Bartlett – see Bartlett window
 - causal – see causal window
 - commonly used, 56, **415**, 420. Also see – tables
 - continuous time – see continuous time windows
 - cosine transform relationships – see tables
 - discrete time – see discrete time windows design, **419**
 - even – see even window
 - filter, 418–419
 - fixed length, 415
 - Hamming – see Hamming window
 - Hanning – see Hanning window
 - Kaiser – see Kaiser window
 - Lanczos – see Lanczos window
 - long – see long window
 - modulated – see modulated window
 - narrow – see narrow window
 - normalized – see normalized window
 - parameter, 439
 - Parzen – see Parzen window
 - short duration – see short duration window
 - sliding – see sliding window
 - table – see tables
 - typical, 415
 - Welch – see Welch window
 - wide – see wide window
- Wise, Gary L., viii, 263, 699, 715
- Wu, Wen–Chung Stewart, viii, 740
- Wunsch, Donald C., viii
- ## X
- x* axis, 564, 628–629
- X-ray, 3, 700, 722, 730–731, 735
- ## Y
- Yang, Y., 527, 741
- yaw, **399**
- Youla, Dante C., 495, 514–515, 742
- ## Z
- z* transform, xi, xiv, 58–60, 421, 423, 646–647
- Zadeh, Lotfi A., 500, 743
- ZAM GTFR, 435
- zero
- crossing, 33, 38, 66, 84, 637, 643, 682, 685, 717
 - input, 113
 - initial condition, 60, 523
 - locus plot, 445–446
 - output, 113
 - mean, 162, 166–167, 187, 192, 194, 201, 204, 288–289, 293, 303, 307, 323, 383, 385, 402–403, 456, 518, 667–668, 676
 - padding, 236, 732
 - phase, 120, 327, 366–367, 691, 726
 - sum property, 245
 - variance, 177
- zeroth order
- sample and hold, 249
 - spectrum, 253, 397, 451, 467, 472
 - spherical Bessel function, 141
 - spherical Hankel transform, 343, 345
 - spectrum, 141, 397, 467, 472
- Zhao, Yunxin, viii, 436, 744
- Zhu, Q. F., 530, 739