1

Electrical and Computer Engineering

Parameters and Characteristics of Discrete Capacitors

Capacitor Type	Range	Rated Voltage, V_R	TTC ppm/°C	Tolerance ±%	Insulation Resistance, MΩµF	Dissipation Factor, %	Dielectric Absorption %	Temperature Range, °C	Comments, Applications	Cost
Polycarbonate	100 pF–30 µF	50–800	±50	10	5×10^5	0.2	0.1	–55/+125	High quality, small, low TC	High
Polyester/Mylar	1000 pF–50 µF	50–600	+400	10	10^5	0.75	0.3	–55/+125	Good, popular	Medium
Polypropylene	100 pF–50 µF	100–800	–200	10	10^5	0.2	0.1	–55/+105	High quality low absorption	High
Polystyrene	10 pF–2.7 µF	100–600	–100	10	10^6	0.05	0.04	–55/+85	High quality, large, low TC, signal filters	Medium
Polysulfone	1000 pF–1 µF		+80	5	10^5	0.3	0.2	–55/+150	High temperature	High
Parylene	5000 pF–1 µF		±100	10	10^5	0.1	0.1	–55/+125		High
Kapton	1000 pF–1 µF		+100	10	10^5	0.3	0.3	–55/+220	High temperature	High
Teflon	1000 pF–2 µF	50–200	–200	10	5×10^6	0.04	0.04	–70/+250	High temperature lowest absorption	High
Mica	5 pF–0.01 µF	100–600	–50	5	2.5×10^4	0.001	0.75	–55/+125	Good at RF, low TC	High
Glass	5 pF–1000 pF	100–600	+140	5	10^6	0.001		–55/+125	Excellent long-term stability	High
Porcelain	100 pF–0.1 µF	50–400	+120	5	5×10^5	0.10	4.2	–55/+125	Good long-term stability	High
Ceramic (NPO)	100 pF–1 µF	50–400	±30	10	5×10^3	0.02	0.75	–55/+125	Active filters, low TC	Medium
Ceramic	10 pF–1 µF	50–30,000						–55/+125	Small, very popular selectable TC	Low
Paper	0.01 µF–10 µF	200–1600	±800	10	5×10^3	1.0	2.5	–55/+125	Motor capacitors	Low
Aluminum	0.1 µF–1.6 F	3–600	+2500	–10/+100	100	10	8.0	–40/+85	Power supply filters short life	High
Tantalum (Foil)	0.1 µF–1000 µF	6–100	+800	–10/+100	20	4.0	8.5	–55/+85	High capacitance small size, low inductance	High
Thin-film	10 pF–200 pF	6–30	+100	10	10^6	0.01		–55/+125		High
Oil	0.1 µF–20 µF	200–10,000				0.5			High voltage filters, large, long life	
Vacuum	1 pF–1000 pF	2000–3600							Transmitters	

From Whitaker, J.C., The origins of AC line disturbances, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 56. Originally published in Filanovsky, I.M., Capacitance and Capacitors, in *The Electronics Handbooks*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1996, p. 371. With permission.

Electrical Properties of Common Insulating Liquids

Liquid	Viscosity cST (37.8°C)	Dielectric Constant (at 60 Hz, 25°C)	Dissipation Factor (at 60 Hz, 100°C)	Breakdown Strength (kV cm^{-1})
Capacitor oil	21	2.2	0.001	>118
Pipe cable oil	170	2.15	0.001	>118
Self-contained cable oil	49.7	2.3	0.001	>118
Heavy cable oil	2365	2.23	0.001	>118
Transformer oil	9.75	2.25	0.001	>128
Alkyl benzene	6.0	2.1	0.0004	>138
Polybutene pipe cable oil	110 (SUS)	2.14 (at 1 MHz)	0.0003	>138
Polybutene capacitor oil	2200 (SUS at 100°C)	2.22 (at 1 MHz)	0.0005	>138
Silicone fluid	50	2.7	0.00015	>138
Castor oil	98 (100°C)	3.74	0.06	>138
$C_8F_{16}O$ fluorocarbon	0.64	1.86	<0.0005	>138

From Whitaker, J.C., The origins of AC line disturbances, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 64. Originally published in Bartnikas, R., Dielectrics and Insulators, in *The Electrical Engineering Handbook*, Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1993, p. 1132. With permission.

Types of Systemwide Protection Equipment Available to Facility Managers and the AC Line Abnormalities That Each Approach Can Handle

System	Type 1	Type 2	Type 3
UPS system and standby generator	All source transients; no load transients	All	All
UPS system	All source transients; no load transients	All	All outages shorter than the battery supply discharge time
Secondary spot network[1]	None	None	Most, depending on the type of outage
Secondary selective network[2]	None	Most	Most, depending on the type of outage
Motor-generator set	All source transients; no load transients	Most	Only brown-out conditions
Shielded isolation transformer	Most source transients; no load transients	None	None
Suppressors, filters, lightning arrestors	Most transients	None	None
Solid-state line voltage regulator/filter	Most source transients; no load transients	Some, depending on the response time of the system	Only brown-out conditions

[1] Dual power feeder network.

[2] Dual power feeder network using a static (solid-state) transfer switch.

From Whitaker, J.C., Power system protection alternatives, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 267. After Key, Lt. Thomas, "The Effects of Power Disturbances on Computer Operation," IEEE Industrial and Commercial Power Systems Conference, Cincinnati, June 7, 1978, and Federal Information Processing Standards Publication No. 94, *Guideline on Electrical Power for ADP Installations*, U.S. Department of Commerce, National Bureau of Standards, Washington, D.C., 1983.

Comparison of System Grounding Methods

Characteristic Assuming No Fault Escalation	System Grounding Method		
	Solidly Grounded	Ungrounded	High Resistance
Operation of overcurrent device on first ground fault	Yes	No	No
Control of internally generated transient overvoltages	Yes	No	Yes
Control of steady-state overvoltages	Yes	No	Yes
Flash hazard	Yes	No	No
Equipment damage from arcing ground-faults	Yes	No	No
Overvoltage (on unfaulted phases) from ground-fault[1]	L-N Voltage	>>L-L-Voltage	L-L Voltage
Can serve line-to-neutral loads	Yes	No	No

[1] L = line, N = neutral

From Whitaker, J.C., Facility grounding, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL:, 1999, p. 373. After IEEE Standard 142, "Recommended Practice for Grounding Industrial and Commercial Power Systems," IEEE, New York, 1982.

Typical Resistivity of Common Soil Types

Type of Soil Resistivity in Ω/cm	Average	Minimum	Maximum
Filled land, ashes, salt marsh	2400	600	7000
Top soils, loam	4100	340	16,000
Hybrid soils	6000	1000	135,000
Sand and gravel	90,000	60,000	460,000

From Whitaker, J.C., Facility grounding, in *AC Power Systems Handbook*, 2nd ed., CRC Press, Boca Raton, FL, 1999, p. 379.

Specifications of Standard Copper Wire

Wire Size AWG	Dia. in Mils	Cir. Mil Area	Turns per Linear Inch[1] Enamel	S.C.E.	D.C.C.	Ohms per 100 ft[2]	Current Carry Capacity[3]	Dia. in mm
1	289.3	83810	—	—	—	0.1239	119.6	7.348
2	257.6	05370	—	—	—	0.1563	94.8	6.544
3	229.4	62640	—	—	—	0.1970	75.2	5.827
4	204.3	41740	—	—	—	0.2485	59.6	5.189
5	181.9	33100	—	—	—	0.3133	47.3	4.621
6	162.0	26250	—	—	—	0.3951	37.5	4.115
7	144.3	20820	—	—	—	0.4982	29.7	3.665
8	128.5	16510	7.6	—	7.1	0.6282	23.6	3.264
9	114.4	13090	8.6	—	7.8	0.7921	18.7	2.906
10	101.9	10380	9.6	9.1	8.9	0.9989	14.8	2.588
11	90.7	8234	10.7	—	9.8	1.26	11.8	2.305
12	80.8	6530	12.0	11.3	10.9	1.588	9.33	2.063
13	72.0	5178	13.5	—	12.8	2.003	7.40	1.828
14	64.1	4107	15.0	14.0	13.8	2.525	5.87	1.628
15	57.1	3257	16.8	—	14.7	3.184	4.65	1.450
16	50.8	2583	18.9	17.3	16.4	4.016	3.69	1.291
17	45.3	2048	21.2	—	18.1	5.064	2.93	1.150
18	40.3	1624	23.6	21.2	19.8	6.386	2.32	1.024
19	35.9	1288	26.4	—	21.8	8.051	1.84	0.912
20	32.0	1022	29.4	25.8	23.8	10.15	1.46	0.812
21	28.5	810	33.1	—	26.0	12.8	1.16	0.723
22	25.3	642	37.0	321.3	30.0	16.14	0.918	0.644
23	22.6	510	41.3	—	37.6	20.36	0.728	0.573
24	20.1	404	46.3	37.6	35.6	25.67	0.577	0.511
25	17.9	320	51.7	—	38.6	32.37	0.458	0.455
26	15.9	254	58.0	46.1	41.8	40.81	0.363	0.406
27	14.2	202	64.9	—	45.0	51.47	0.288	0.361
28	12.6	160	72.7	54.6	48.5	64.9	0.228	0.321
29	11.3	127	81.6	—	51.8	81.83	0.181	0.286
30	10.0	101	90.5	64.1	55.5	103.2	0.144	0.255
31	8.9	50	101	—	59.2	130.1	0.114	0.227
32	8.0	63	113	74.1	61.6	164.1	0.090	0.202
33	7.1	50	127	—	66.3	206.9	0.072	0.180
34	6.3	40	143	86.2	70.0	260.9	0.057	0.160
35	5.6	32	158	—	73.5	329.0	0.045	0.143
36	5.0	25	175	103.1	77.0	414.8	0.036	0.127
37	4.5	20	198	—	80.3	523.1	0.028	0.113
38	4.0	16	224	116.3	83.6	659.6	0.022	0.101
39	3.5	12	248	—	86.6	831.8	0.018	0.090

Notes:

[1] Based on 25.4 mm.

[2] Ohms per 1000 ft measured at 20°C.

[3] Current carrying capacity at 700 C.M./A.

From Whitaker, J.C., Conversion tables, in *AC Power Systems Handbook*, 2nd., CRC Press, Boca Raton, FL, 1999, pp. 528–529.

Parameters of Some First-Generation Cellular Standards

Parameters	AMPS	C450	NMT 450	NTT	TACS
Tx Frequency (MHz)					
Mobile	824–849	450–455.74	453–457.5	925–940	890–915
Base Station	869–894	460–465.74	463–467.5	870–885	935–960
Channel bandwidth (kHz)	30	20	25	25	25
Spacing between forward and reverse channels (MHz)	45	10	10	55	45
Speech signal FM deviation	±12	±5	±5	±5	±9.5
Control signal data rate (kbps)	10	5.28	1.2	0.3	8
Handoff decision is based on	Power received at base	Round-trip delay	Power received at base	Power received at base	Power received at base

From Godara, L.C., Cellular systems, in *Handbook of Antennas in Wireless Communications*, Godara, L.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-15.

Parameters of Some Second-Generation Cellular Standards

Parameters	IS-54	GSM	IS-95	PDC
TX frequencies (MHz)				
Mobile	824–849	890–915	824–849	940–956 and 1429–1453
Base station	869–894	935–960	869–894	810–826 and 1477–1501
Channel bandwidth (kHz)	30 kHz	200 kHz	1250 kHz	25 kHz
Spacing between forward and reverse channels (MHz)	45	45	45	30/48
Modulation	π/4 DQPSK	GMSK	BPSK/QPSK	π/4 DQPSK
Frame duration (ms)	40	4.615	20	20

From Godara, L.C., Cellular systems, in *Handbook of Antennas in Wireless Communications*, Godara, L.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-16.

Comparison of Satellite Systems as a Function of Orbit

Characteristic	LEO	MEO	GEO
Satellite height (km)	600–1,500	9,000–11,000	35,800
Orbital period (hr)	1–2	6–8	24
Number of satellites	40–80	8–20	2–4
Two-way propagation delay (ms)	10–15	150–250	480–540
Satellite life (years)	3–7	10–15	10–15
Elevation angle	Medium	Best	Good
Visibility of satellite	Short	Medium	Permanent
Handheld terminal	Possible	Possible	Restricted
Handover	Frequent	Infrequent	None
Cost of satellite	Maximum	Minimum	Medium
Gateway cost	Highest	Medium	Lowest
Network complexity	Complex	Medium	Simplest
Radio frequency output power	Low	Medium	High
Propagation loss	Low	Medium	High

From Ryan, M.J., Satellite-based mobile communications, in *Handbook of Antennas in Wireless Communications,* Godara, L.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **2**-8.

Summary of Transmission Media Characteristics

Cable Type	Twisted Shielded Pair
Capacitance	30.0 pF/ft max — wire to wire
Characteristic Impedance	70.0 to 85.0 ohms at 1 MHz
Cable Attenuation	1.5 dbm/100 ft at 1 MHz
Cable Twists	4 twists per foot maximum
Shield Coverage	90% minimum
Cable Termination	Cable impedance (±2%)
Direct Coupled Stub Length	Maximum of 1 ft
Transformer Coupled Stub Length	Maximum of 20 ft

From deLong, C., AS 15531/MIL-STD-1553B digital time division command/response multiplex data bus, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, , p. **1**-5.

CSDB Physical Characteristics

Modulation Technique	Non-Return to Zero (NRZ)
Logic Sense for Logic “0”	Line B Positive with Respect to Line A
Logic Sense for Logic “1”	Line A Positive with Respect to Line B
Bus Receiver	High Impedance, Differential Input
Bus Transmitter	Differential Line Driver
Bus Signal Rates	Low Speed: 12,500 bps High Speed: 50,000 bps
Signal Rise-Time and Fall-Time	Low Speed: 8 μs High-Speed: 0.8–1.0 μs
Receiver Capacitance Loading	Typical: 600 pF Maximum: 1,200 pF
Transmitter Driver Capability	Maximum: 12,000 pF

From Harrison, L.H., Commercial standard digital bus, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, p. **3**-4. Originally published in *Commercial Standard Digital Bus,* 8th ed., Collins General Aviation Division, Rockwell International Corporation, Cedar Rapids, IA, January 30, 1991.

Sensor Data Required for Full Flight Regime Operation

Input Data	Data Source
Attitude	Pitch and Roll Angles — 2 independent sources
Airspeed	Calibrated Airspeed
	Low Speed Awareness Speed(s) (e.g., Vstall)
	High Speed Awareness Speed(s) (e.g., Vmo)
Altitude	Barometric Altitude (pressure altitude corrected with altimeter setting)
	Radio Altitude
Vertical Speed	Vertical Speed (inertial if available, otherwise raw air data)
Slip/Skid	Lateral Acceleration
Heading	Magnetic Heading
	True Heading or other heading (if selectable)
	Heading Source Selection (if other than Magnetic selectable)
Navigation	Selected Course
	VOR Bearing/Deviation
	DME Distance
	Localizer Deviation
	Glideslope Deviation
	Marker Beacons
	Bearings/Deviations/Distances for any other desired nav signals (e.g., ADF, TACAN, RNAV/FMS)
Reference Information	Selected Airspeed
	Selected Altitude
	Selected Heading
	Other Reference Speed Information (e.g., V_1, V_R, Vapch)
	Other Reference Altitude Information (e.g., landing minimums [DH/MDA], altimeter setting)
Flight Path	Pitch Angle
	Roll Angle
	Heading (Magnetic or True, same as Track)
	Ground Speed (inertial or equivalent)
	Track Angle (Magnetic or True, same as Heading)
	Vertical Speed (inertial or equivalent)
	Pitch Rate, Yaw Rate
Flight Path Acceleration	Longitudinal Acceleration
	Lateral Acceleration
	Normal Acceleration
	Pitch Angle
	Roll Angle
	Heading (Magnetic or True, same as Track)
	Ground Speed (inertial or equivalent)
	Track Angle (Magnetic or True, same as Heading)
	Vertical Speed (inertial or equivalent)
Automatic Flight Control System	Flight Director Guidance Commands
	Autopilot/Flight Director Modes
	Autothrottle Modes
Miscellaneous	Wind Speed
	Wind Direction (and appropriate heading reference)
	Mach
	Windshear Warning(s)
	Ground Proximity Warning(s)
	TCAS Resolution Advisory Information

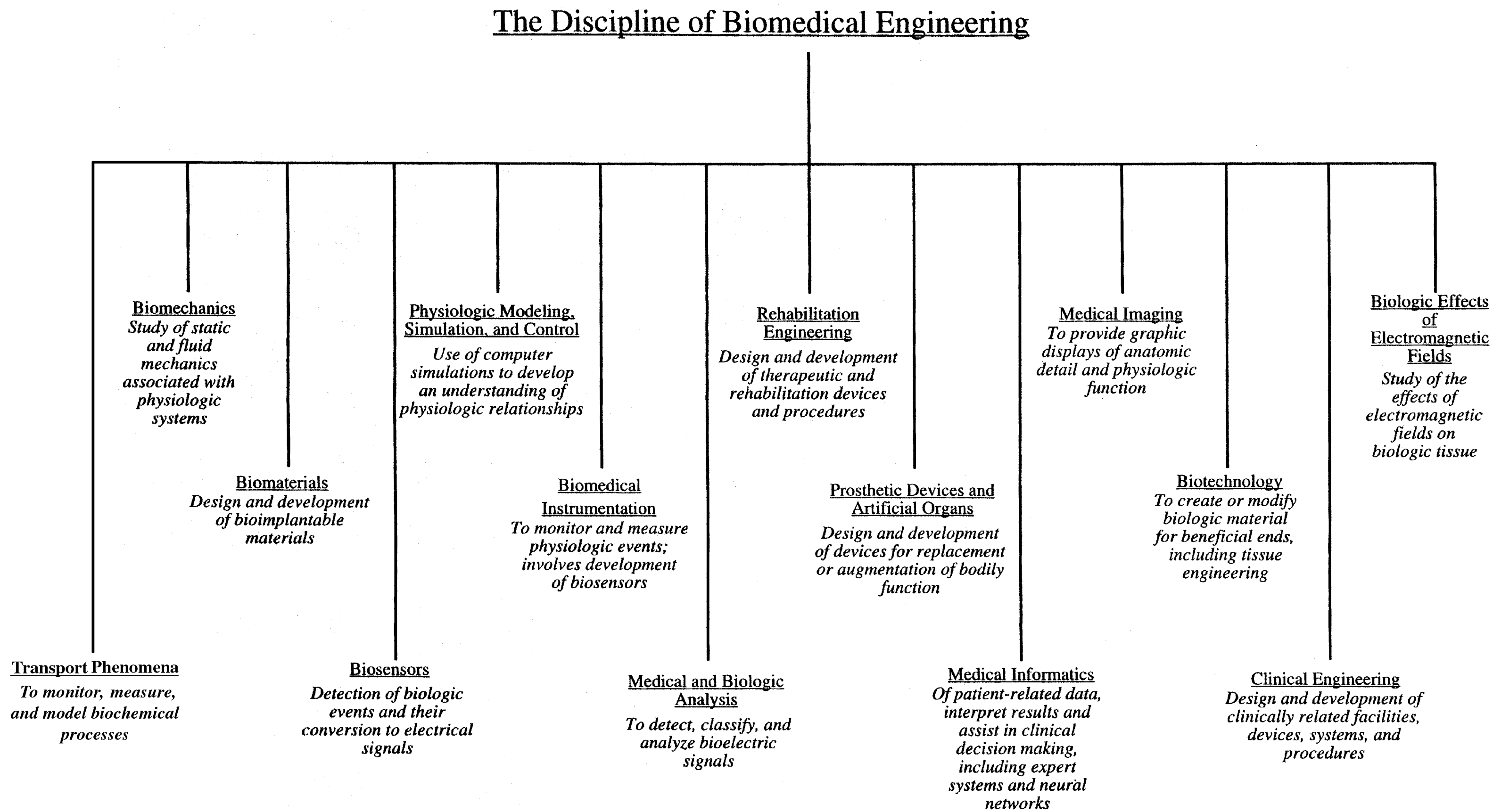
From Wood, R.B. and Howells, P.J., Head-up displays, in *The Avionics Handbook*, Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, p. **4**-14.

Categorization of Fault-Tolerant Software Techniques

Multiversion Software
N-Version Program
Cranfield Algorithm for Fault-Tolerance (CRAFT) Food Taster
Distinct and Dissimilar Software
Recovery Blocks
Deadline Mechanism
Dissimilar Backup Software
Exception Handlers
Hardened Kernel
Robust Data Structures and Audit Routines
Run Time Assertions[a]
Hybrid Multiversion Software and Recovery Block Techniques
Tandem
Consensus Recovery Blocks

[a] Not a complete fault-tolerant software technique as it only detects errors.

From Hitt, E.F. and Mulcare, D., Fault-tolerant avionics, in *The Avionics Handbook,* Spitzer, C.R., Ed., CRC Press, Boca Raton, FL, 2001, p. **28**-20. Originally from Hitt, E. et al., *Study of Fault-Tolerant Software Technology,* NASA CR 172385.



From *The Biomedical Engineering Handbook*, 2nd ed., Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000. p. x.

Hematocytes

Cell Type	Number Cells per mm^3 Blood*	Corpuscular Diameter (μm)*	Corpuscular Surface Area ($μm^2$)*	Corpuscular Volume ($μm^3$)*	Mass Density (g/cm^3)*	Percent Water*	Percent Protein*	Percent Extractives*†
Erythrocytes (red blood cells)	4.2–5.4 $\times 10^6$ ♀ 4.6–6.2 $\times 10^6$ ♂ (5×10^6)	6–9 (7.5) Thickness 1.84–2.84 "Neck" 0.81–1.44	120–163 (140)	80–100 (90)	1.089–1.100 (1.098)	64–68 (66)	29–35 (32)	1.6–2.8 (2)
Leukocytes (white blood cells)	4000–11000 (7500)	6–10	300–625	160–450	1.055–1.085	52–60 (56)	30–36 (33)	4–18 (11)
Granulocytes								
Neutrophils: 55–70% WBC (65%)	$2–6 \times 10^3$ (4875)	8–8.6 (8.3)	422–511 (467)	268–333 (300)	1.075–1.085 (1.080)	—	—	—
Eosinophils: 1–4% WBC (3%)	45–480 (225)	8–9 (8.5)	422–560 (491)	268–382 (321)	1.075–1.085 (1.080)	—	—	—
Basophils: 0–1.5% WBC (1%)	0–113 (75)	7.7–8.5 (8.1)	391–500 (445)	239–321 (278)	1.075–1.085 (1.080)	—	—	—
Agranulocytes								
Lymphocytes: 20–35% WBC (25%)	1000–4800 (1875)	6.75–7.34 (7.06)	300–372 (336)	161–207 (184)	1.055–1.070 (1.063)	—	—	—
Monocytes: 3–8% WBC (6%)	100–800 (450)	9–9.5 (9.25)	534–624 (579)	382–449 (414)	1.055–1.070 (1.063)	—	—	—
Thrombocytes (platelets) (2.675×10^5)	(1.4 ♂), 2.14 (♀)–5 $\times 10^5$	2–4 (3) Thickness 0.9–1.3	16–35 (25)	5–10 (7.5)	1.04–1.06 (1.05)	60–68 (64)	32–40 (36)	Neg.

*Normal physiologic range, with "typical" value in parentheses.

†Extractives include mostly minerals (ash), carbohydrates, and fats (lipids).

From Schneck, D.J., An outline of cardiovascular structure and function, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1., Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-2.

Plasma

Constituent	Concentration Range (mg/dl plasma)	Typical Plasma Value (mg/dl)	Molecular Weight Range	Typical Value	Typical size (nm)
Total protein, 7% by weight	6400–8300	7245	21,000–1,200,000	—	—
Albumin (56% TP)	2800–5600	4057	66,500–69,000	69,000	15 × 4
α_1-*Globulin* (5.5% TP)	300–600	400	21,000–435,000	60,000	5–12
α_2-*Globulin* (7.5% TP)	400–900	542	100,000–725,000	200,000	50–500
β-*Globulin* (13% TP)	500–1230	942	90,000–1,200,000	100,000	18–50
γ-*Globulin* (12% TP)	500–1800	869	150,000–196,000	150,000	23 × 4
Fibrinogen (4% TP)	150–470	290	330,000–450,000	390,000	(50–60) × (3–8)
Other (2% TP)	70–210	145	70,000–1,000,000	200,000	(15–25) × (2–6)
Inorganic ash, 0.95% by weight	930–1140	983	20–100	—	— (Radius)
Sodium	300–340	325	—	22.98977	0.102 (Na^+)
Potassium	13–21	17	—	39.09800	0.138 (K^+)
Calcium	8.4–11.0	10	—	40.08000	0.099 (Ca^{2+})
Magnesium	1.5–3.0	2	—	24.30500	0.072 (Mg^{2+})
Chloride	336–390	369	—	35.45300	0.181 (Cl^-)
Bicarbonate	110–240	175	—	61.01710	0.163 (HCO_3^-)
Phosphate	2.7–4.5	3.6	—	95.97926	0.210 (HPO_4^{2-})
Sulfate	0.5–1.5	1.0	—	96.05760	0.230 (SO_4^{2-})
Other	0–100	80.4	20–100	—	0.1–0.3
Lipids (fats), 0.80% by weight	541–1000	828	44,000–3,200,000	= Lipoproteins	Up to 200 or more
Cholesterol (34% TL)	12–105 "free" 72–259 esterified, 84–364 "total"	59 224 283	386.67	Contained mostly in intermediate to LDL β-lipoproteins; higher in women	
Phospholipid (35% TL)	150–331	292	690–1010	Contained mainly in HDL to VHDL α_1-lipoproteins	
Triglyceride (26% TL)	65–240	215	400–1370	Contained mainly in VLDL α_2-lipoproteins and chylomicrons	
Other (5% TL)	0–80	38	280–1500	Fat-soluble vitamins, prostaglandins, fatty acids	
Extractives, 0.25% by weight	200–500	259	—	—	—
Glucose	60–120, fasting	90	—	180.1572	0.86 D
Urea	20–30	25	—	60.0554	0.36 D
Carbohydrate	60–105	83	180.16–342.3	—	0.74–0.108 D
Other	11–111	61	—	—	—

From Schneck, D.J., An outline of cardiovascular structure and function, in *The Biomedical Engineering Handbook*, 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-3.

Arterial System*

Blood Vessel Type	(Systemic) Typical Number	Internal Diameter Range	Length Range†	Wall Thickness	Systemic Volume	(Pulmonary) Typical Number	Pulmonary Volume
Aorta	1	1.0–3.0 cm	30–65 cm	2–3 mm	156 ml	—	—
Pulmonary artery	—	2.5–3.1 cm	6–9 cm	2–3 cm	—	1	52 ml
Wall morphology: Complete tunica adventitia, external elastic lamina, tunica media, internal elastic lamina, tunica intima, subendothelium, endothelium, and vasa vasorum vascular supply							
Main branches	32	5 mm–2.25 cm	3.3–6 cm	≃2 mm	83.2 ml	6	41.6 ml
(Along with the aorta and pulmonary artery, the largest, most well-developed of all blood vessels)							
Large arteries	288	4.0–5.0 mm	1.4–2.8 cm	≃1 mm	104 ml	64	23.5 ml
(A well-developed tunica adventitia and vasa vasorum, although wall layers are gradually thinning)							
Medium arteries	1152	2.5–4.0 mm	1.0–2.2 cm	≃0.75 mm	117 ml	144	7.3 ml
Small arteries	3456	1.0–2.5 mm	0.6–1.7 cm	≃0.50 mm	104 ml	432	5.7 ml
Tributaries	20,736	0.5–1.0 mm	0.3–1.3 cm	≃0.25 mm	91 ml	5184	7.3 ml
(Well-developed tunica media and external elastic lamina, but tunica adventitia virtually nonexistent)							
Small rami	82,944	250–500 μm	0.2–0.8 cm	≃125 μm	57.2 ml	11,664	2.3 ml
Terminal branches	497,664	100–250 μm	1.0–6.0 mm	≃60 μm	52 ml	139,968	3.0 ml
(A well-developed endothelium, subendothelium, and internal elastic lamina, plus about two to three 15-μm-thick concentric layers forming just a very thin tunica media; no external elastic lamina)							
Arterioles	18,579,456	25–100 μm	0.2–3.8 mm	≃20–30 μm	52 ml	4,094,064	2.3 ml
Wall morphology: More than one smooth muscle layer (with nerve association in the outermost muscle layer), a well-developed internal elastic lamina; gradually thinning in 25- to 50-μm vessels to a single layer of smooth muscle tissue, connective tissue, and scant supporting tissue.							
Metarterioles	238,878,720	10–25 μm	0.1–1.8 mm	≃5–15 μm	41.6 ml	157,306,536	4.0 ml
(Well-developed subendothelium; discontinuous contractile muscle elements; one layer of connective tissue)							
Capillaries	16,124,431,360	3.5–10 μm	0.5–1.1 mm	≃0.5–1 μm	260 ml	3,218,406,696	104 ml
(Simple endothelial tubes devoid of smooth muscle tissue; one-cell-layer-thick walls)							

*Vales are approximate for a 68.7-kg individual having a total blood volume of 5200 ml.

†Average uninterrupted distance between branch origins (except aorta and pulmonary artery, which are total length).

From Schneck, D.J., An outline of cardiovascular structure and functions, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-8.

Venous System

Blood Vessel Type	(Systemic) Typical Number	Internal Diameter Range	Length Range	Wall Thickness	Systemic Volume	(Pulmonary) Typical Number	Pulmonary Volume
Postcapillary venules	4,408,161,734	8–30 μm	0.1–0.6 mm	1.0–5.0 μm	166.7 ml	306,110,016	10.4 ml
(Wall consists of thin endothelium exhibiting occasional pericytes (pericapillary connective tissue cells) which increase in number as the vessel lumen gradually increases)							
Collecting venules	160,444,500	30–50 μm	0.1–0.8 mm	5.0–10 μm	161.3 ml	8,503,056	1.2 ml
(One complete layer of pericytes, one complete layer of veil cells (veil-like cells forming a thin membrane), occasional primitive smooth muscle tissue fibers that increase in number with vessel size)							
Muscular venules	32,088,900	50–100 μm	0.2–1.0 mm	10–25 μm	141.8 ml	3,779,136	3.7 ml
(Relatively thick wall of smooth muscle tissue)							
Small collecting veins	10,241,508	100–200 μm	0.5–3.2 mm	≃30 μm	329.6 ml	419,904	6.7 ml
(Prominent tunica media of continuous layers of smooth muscle cells)							
Terminal branches	496,900	200–600 μm	1.0–6.0 mm	30–150 μm	206.6 ml	34,992	5.2 ml
(A well-developed endothelium, subendothelium, and internal elastic lamina; well-developed tunica media but fewer elastic fibers than corresponding arteries and much thinner walls)							
Small veins	19,968	600 μm–1.1 mm	2.0–9.0 mm	≃0.25 mm	63.5 ml	17,280	44.9 ml
Medium veins	512	1–5 mm	1–2 cm	≃0.50 mm	67.0 ml	144	22.0 ml
Large veins	256	5–9 mm	1.4–3.7 cm	≃0.75 mm	476.1 ml	48	29.5 ml
(Well-developed wall layers comparable to large arteries but about 25% thinner)							
Main branches	224	9.0 mm–2.0 cm	2.0–10 cm	≃1.00 mm	1538.1 ml	16	39.4 ml
(Along with the vena cava and pulmonary veins, the largest, most well-developed of all blood vessels)							
Vena cava	1	2.0–3.5 cm	20–50 cm	≃1.50 mm	125.3 ml	—	—
Pulmonary veins	—	1.7–2.5 cm	5–8 cm	≃1.50 mm	—	4	52 ml
Wall morphology: Essentially the same as comparable major arteries but a much thinner tunica intima, a much thinner tunica media, and a somewhat thicker tunica adventitia; contains a vasa vasorum							

Total systemic blood volume: 4394 ml—84.5% of total blood volume; 19.5% in arteries (~3:2 large:small), 5.9% in capillaries, 74.6% in veins (~3:1 large:small); 63% of volume is in vessels greater than 1 mm internal diameter

Total pulmonary blood volume: 468 ml—9.0% of total blood volume; 31.8% in arteries, 22.2% in capillaries, 46% in veins; 58.3% of volume is in vessels greater than 1 mm internal diameter; remainder of blood in heart, about 338 ml (6.5% of total blood volume)

From Schneck, D.J., An outline of cardiovascular structure and functions, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-8.

Main Endocrine Glands and the Hormones They Produce and Release

Gland	Hormone	Chemical Characteristics
Hypothalamus/median eminence	Thyrotropin-releasing hormone (TRH)	Peptides
	Somatostatin	
	Gonadotropin-releasing hormone	Amine
	Growth hormone-releasing hormone	
	Corticotropin-releasing hormone	
	Prolactin inhibitor factor	
Anterior pituitary	Thyrotropin (TSH)	Glycoproteins
	Luteinizing hormone	
	Follicle-stimulating hormone (FSH)	Proteins
	Growth hormone	
	Prolactin	
	Adrenocorticotropin (ACTH)	
Posterior pituitary	Vasopressin (antidiuretic hormone, ADH)	
	Oxytocin	Peptides
Thyroid	Triidothyronine (T3)	Tyrosine derivatives
	Thyroxine (T4)	
Parathyroid	Parathyroid hormone (PTH)	Peptide
Adrenal cortex	Cortisol	Steroids
	Aldosterone	
Adrenal medulla	Epinephrine	Catecolamines
	Norepinephrine	
Pancreas	Insulin	Proteins
	Glucagon	
	Somatostatin	
Gonads: Testes	Testosterone	Steroids
Ovaries	Oestrogen	
	Progesterone	

From Cramp, D.G. and Carson, E.R., Endocrine system, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **2**-3.

Typical Lung Volumes for Normal, Healthy Males

Lung Volume	Normal Values	
Total lung capacity (TLC)	6.0×10^{-3} m^3	(6,000 cm^3)
Residual volume (RV)	1.2×10^{-3} m^3	(1,200 cm^3)
Vital capacity (VC)	4.8×10^{-3} m^3	(4,800 cm^3)
Inspiratory reserve volume (IRV)	3.6×10^{-3} m^3	(3,600 cm^3)
Expiratory reserve volume (ERV)	1.2×10^{-3} m^3	(1,200 cm^3)
Functional residual capacity (FRC)	2.4×10^{-3} m^3	(2,400 cm^3)
Anatomic dead volume (V_D)	1.5×10^{-4} m^3	(150 cm^3)
Upper airways volume	8.0×10^{-5} m^3	(80 cm^3)
Lower airways volume	7.0×10^{-5} m^3	(70 cm^3)
Physiologic dead volume (V_D)	1.8×10^{-4} m^3	(180 cm^3)
Minute volume ($\dot{V}_e$) at rest	1.0×10^{-4} m^3/s	(6,000 cm^3/min)
Respiratory period (T) at rest	4s	
Tidal volume (V_T) at rest	4.0×10^{-4} m^3	(400 cm^3)
Alveolar ventilation volume (V_A) at rest	2.5×10^{-4} m^3	(250 cm^3)
Minute volume during heavy exercise	1.7×10^{-3} m^3/s	(10,000 cm^3/min)
Respiratory period during heavy exercise	1.2 s	
Tidal volume during heavy exercise	2.0×10^{-3} m^3	(2,000 cm^3)
Alveolar ventilation volume during exercise	1.8×10^{-3} m^3	(1,820 cm^3)

From Johnson, A.T., Lausted, C.G., and Bronzino, J.D., Respiratory system, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **7**-7.

Molecular Masses, Gas Constants, and Volume Fractions for Air and Constituents

Constituent	Molecular Mass kg/mol	Gas Constant, N·m/(mol·K)	Volume Fraction in Air, m^3/m^3
Air	29.0	286.7	1.0000
Ammonia	17.0	489.1	0.0000
Argon	39.9	208.4	0.0093
Carbon dioxide	44.0	189.0	0.0003
Carbon monoxide	28.0	296.9	0.0000
Helium	4.0	2078.6	0.0000
Hydrogen	2.0	4157.2	0.0000
Nitrogen	28.0	296.9	0.7808
Oxygen	32.0	259.8	0.2095

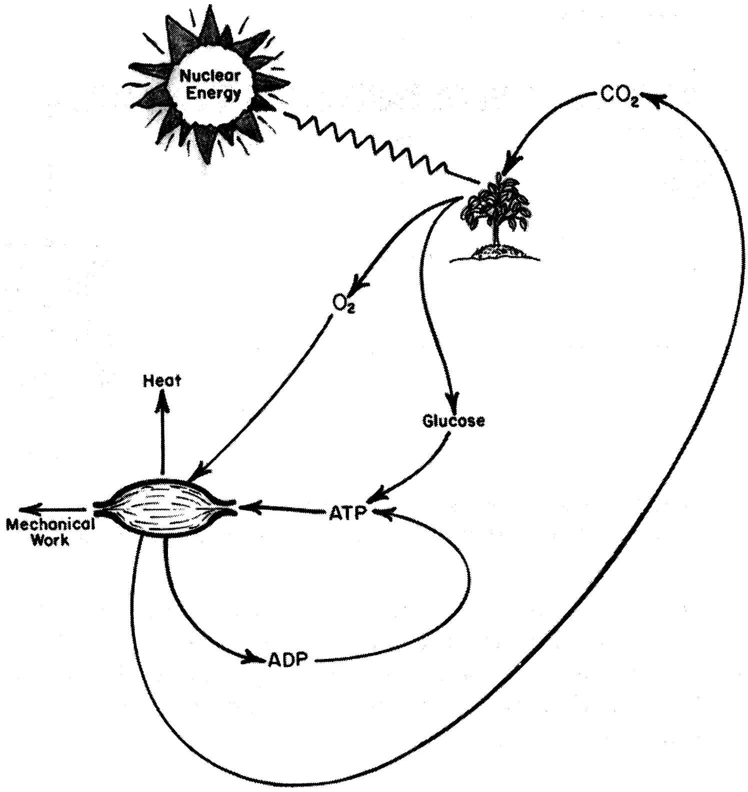
Note: Universal gas constant is 8314.43 N·m/kg·mol·K.

From Johnson, A.T., Lausted, C.G., and Bronzino, J.D., Respiratory system, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **7**-9.

Conductivity Values for Cardiac Bidomain

S/mm	Clerc [1976]	Roberts [1982]
g_{ix}	1.74×10^{-4}	3.44×10^{-4}
g_{iy}	1.93×10^{-5}	5.96×10^{-5}
g_{ax}	6.25×10^{-4}	1.17×10^{-4}
g_{ay}	2.36×10^{-4}	8.02×10^{-5}

From Plonsey, R., Volume conductor theory, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **9**-5.



Schematic of energy transformations leading to muscular mechanical work. (From Johnson, A.T. and Hurley, B.F., Factors affecting mechanical work in humans, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **27**-2.)

Typical Values and Estimates for Young's Modulus *E*

Compact bone	20	GPa
Keratin	3	GPa
Basilar membrane fibers	1.9	GPa
Microtubules	1.2	GPa
Collagen	1	GPa
Reissner's membrane	60	MPa
Actin	50	MPa
Red blood cell, extended (assuming thickness = 10 nm)	45	MPa
Rubber, elastin	4	MPa
Basilar membrane ground substance	200	kPa
Tectorial membrane	30	kPa
Jell-O	3	kPa
Henson's cells	1	kPa

From Steele, C.R., Baker, G.J., Tolomeo, J.A., and Zetes-Tolomeo, D.E., Cochlear mechanics, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **35**-4.

Properties of Bone, Teeth, and Biomaterials

Material	Young's modulus E[GPa]	Density ρ (g/cm³)	Strength (MPa)
Hard Tissue	17	1.8	130 (tension)
Tooth, bone, human compact bone, longitudinal direction			
Tooth dentin	18	2.1	138 (compression)
Tooth enamel	50	2.9	
Polymers			
Polyethylene (UHMW)	1	0.94	30 (tension)
Polymethyl methacrylate, PMMA	3	1.1	65 (tension)
PMMA bone cement	2	1.18	30 (tension)
Metals			
316L Stainless steel (wrought)	200	7.9	1000 (tension)
Co-Cr-Mo (cast)	230	8.3	660 (tension)
Co Ni Cr Mo (wrought)	230	9.2	1800 (tension)
Ti6A14V	110	4.5	900 (tension)
Composites			
Graphite-epoxy (unidirectional fibrous, high modulus)	215	1.63	1240 (tension)
Graphite-epoxy (quasi-isotropic fibrous)	46	1.55	579 (tension)
Dental composite resins (particulate)	10-16		170-260 (compression)
Foams			
Polymer foams	10^{-4}–1	0.002–0.8	0.01–1 (tension)

From Lakes, R., Composite biomaterials, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **40**-6.

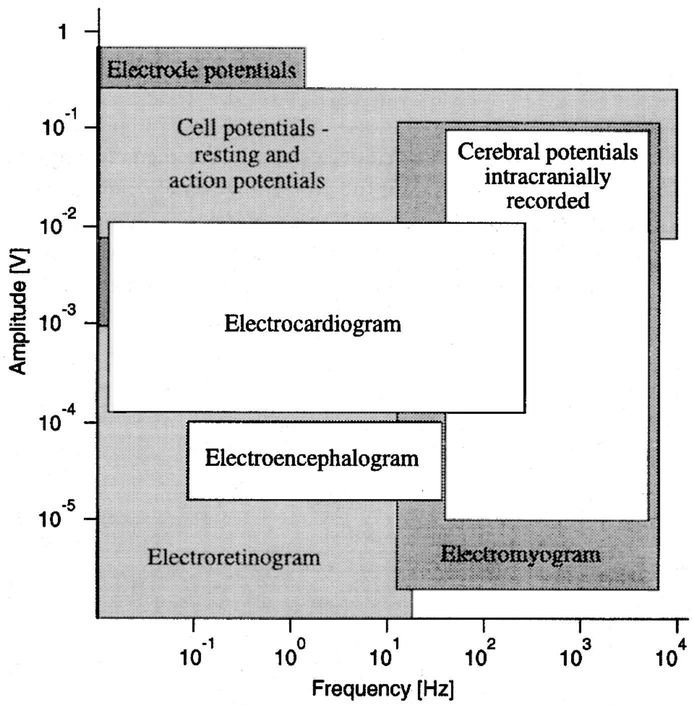
Biomedical Signals

Classification	Acquisition	Frequency Range	Dynamic Range	Comments
Bioelectric				
Action potential	Microelectrodes	100 Hz–2 kHz	10 μV–100 mV	Invasive measurement of cell membrane potential
Electroneurogram (ENG)	Needle electrode	100 Hz–1 kHz	5 μV–10 mV	Potential of a nerve bundle
Electroretinogram (ERG)	Microelectrode	0.2–200 Hz	0.5 μV–1 mV	Evoked flash potential
Electro-oculogram (EOG)	Surface electrodes	dc–100 Hz	10 μV–5 mV	Steady-corneal-retinal potential
Electroencephalogram (EEG)				
Surface	Surface electrodes	0.5–100 Hz	2–100 μV	Multichannel (6–32) scalp potential
Delta range		0.5–4 Hz		Young children, deep sleep and pathologies
Theta range		4–8 Hz		Temporal and central areas during alert states
Alpha range		8–13 Hz		Awake, relaxed, closed eyes
Beta range		13–22 Hz		
Sleep spindles		6–15 Hz	50–100 μV	Bursts of about 0.2 to 0.6 s
K-complexes		12–14 Hz	100–200 μV	Bursts during moderate and deep sleep
Evoked potentials (EP)	Surface electrodes		0.1–20 μV	Response of brain potential to stimulus
Visual (VEP)		1–300 Hz	1–20 μV	Occipital lobe recordings, 200-ms duration
Somatosensory (SEP)		2 Hz–3 kHz		Sensory cortex
Auditory (AEP)		100 Hz–3 kHz	0.5–10 μV	Vertex recordings

Biomedical Signals (continued)

Classification	Acquisition	Frequency Range	Dynamic Range	Comments
Electrocorticogram	Needle electrodes	100 Hz–5 kHz		Recordings from exposed surface of brain
Electromyography (EMG)				
Single-fiber (SFEMG)	Needle electrode	500 Hz–10 kHz	1–10 μV	Action potentials from single muscle fiber
Motor unit action potential (MUAP)	Needle electrode	5 Hz–10 kHz	100 μV–2 mV	
Surface EMG (SEMG)	Surface electrodes			
Skeletal muscle		2–500 Hz	50 μV–5 mV	
Smooth muscle		0.01–1 Hz		
Electrocardiogram (ECG)	Surface electrodes	0.05–100 Hz	1–10 mV	
High-Frequency ECG	Surface electrodes	100 Hz–1 kHz	100 μV–2 mV	Notchs and slus waveforms superimposed on the ECG.

From Cohen, A., Biomedical signals: Origin and dynamic characteristics; frequency-domain analysis, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **52**-4.



Amplitudes and spectral range of some important biosignals. The various biopotentials completely cover the area 10^{-6} V to almost 1 V and from dc to 10 kHz. (From Nagel, J.H., Biopotential amplifiers, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 1, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **70**-5.)

Representative Thermal Property Values

Tissue	Thermal Conductivity (W/m-K)	Thermal Diffusivity (m^2/s)	Perfusion (m^3/m^3-sec)
Aorta	0.461 [16]	1.25×10^{-7} [16]	
Fat of spleen	0.3337 [44]	1.314×10^{-7} [44]	
Spleen	0.5394 [44]	1.444×10^{-7} [44]	0.023 [45]
Pancreas	0.5417 [44]	1.702×10^{-7} [44]	0.0091 [45]
Cerebral cortex	0.5153 [44]	1.468×10^{-7} [44]	0.0067 [46]
Renal cortex	0.5466 [44]	1.470×10^{-7} [44]	0.077 [47]
Myocardium	0.5367 [44]	1.474×10^{-7} [44]	0.0188 [48]
Liver	0.5122 [44]	1.412×10^{-7} [44]	0.0233 [49]
Lung	0.4506 [44]	1.307×10^{-7} [44]	
Adenocarcinoma of breast	0.5641 [44]	1.436×10^{-7} [44]	
Resting muscle bone	0.478 [50]	1.59×10^{-7} [50]	0.0007 [48]
Whole blood (21°C)	0.492 [50]	1.19×10^{-7} [50]	
Plasma (21°C)	0.570 [50]	1.21×10^{-7} [50]	
Water	0.628 [6]	1.5136×10^{-7} [6]	

All conductivities and diffusivities are from humans at 37°C except the value for skeletal muscle which is from sheep at 21°C. Perfusion values are from various mammals as noted in the references. Significant digits do not imply accuracy. The temperature coefficient for thermal conductivity ranges from –0.000254 to 0.0039 W/m-K-°C with 0.001265 W/m-K-°C typical of most tissues as compared to 0.001575 W/m-K-°C for water [44]. The temperature coefficient for thermal diffusivity ranges from -4.9×10^{-10} m^2/s-°C to 8.4×10^{-10} m^2/s-°C with 5.19×10^{-10} m^2/s-°C typical of most tissues as compared to 4.73×10^{-10} m^2/s-°C for water [44]. The values provided in this table are representative values presented for tutorial purposes. The reader is referred to the primary literature for values appropriate for specific design applications.

From Baish, J.W., Microvascular heat transfer, in *The Biomedical Engineering Handbook,* 2nd ed., vol. 2, Bronzino, J.D., Ed., CRC Press, Boca Raton, FL, 2000, p. **98**-6.

Summary of Several Types of Wavelet Bases for $L^2(R)$

Type of Wavelet	Decay of $\psi(t)$ in Time	Regularity of $\psi(t)$ in Time	Type of Wavelet Basis
Stromberg, 1982	Exponential	$\psi(t) \in C^k$; k can be chosen arbitrarily large	Orthonormal
Meyer, 1985	Faster than any chosen inverse polynomial	$\psi(t) \in C^\infty$ (band limited)	Orthonormal
Battle–Lemarié, 1987, 1988 (splines)	Exponential	$\psi(t) \in C^k$; k can be chosen arbitarily large	Orthonormal
Daubechies, 1988	Compactly supported	$\psi(t) \in C^\alpha$; α can be chosen as large as we please	Orthonormal

From Vaidyanathan, P.P. and Djokovic, I., Wavelet transforms, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 212.

Debye Temperature and Resistivity of Nonmagnetic Metals

Metal	ρ_{20} at $T = 293$ K [$10^{-8}\,\Omega * \text{m}$]	Θ [K]	0.15 Θ [K]	ρ at Θ [$10^{-8}\,\Omega * \text{m}$]
Ag	1.62	214	32	1.16
Cu	1.68	320	48	1.94
Au	2.22	160	24	1.17
Al	2.73	374	56	3.79
Zn	6.12	180	27	3.65
Pt	10.6	220	33	7.91
Pb	20.8	84.5	12.7	5.5
W	5.39	346	52	6.76

From Nowak, S., Resistor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 284.

Comparison of Capacitor Dielectric Constants

Dielectric	ε_r (Dielectric Constant)
Air or vacuum	1.0
Paper	2.0–6.0
Plastic	2.1–6.0
Mineral oil	2.2–2.3
Silicone oil	2.7–2.8
Quartz	3.8–4.4
Glass	4.8–8.0
Porcelain	5.1–5.9
Mica	5.4–8.7
Aluminium oxide	8.4
Tantalum pentoxide	26
Ceramic	12–400,000

From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 295. Originally from *The Electrical Engineering Handbook,* Dorf, R., Ed., CRC Press, Boca Raton, FL, 1993.

υ′ Index of Various Capacitors

Capacitor Definition	Main Parameters	υ′ [$\text{cm}^3/\mu\text{F}$]
Variable air	500 pF/250 V	200,000
Mica	10 nF/500 V	250
Ceramic (rutile)	1000 pF/500 V	600
Ferroelectronic	40 nF /250 V	50
Ferroelectric multilayer	0.68 μF/50 V	1.5
Polystyrene	2 μF/160 V	300
Polyester (mylar)	0.1 μF/160 V	12.4
Polycarbonate — metalized	0.15 μF/160 V	5.6
Electrolytic Al(HV)[a]	40 μF/350 V	1.3
Electrolytic Al(LV)[a]	120 μF/7 V	0.008
"Golden" capacitor	1 F/5.5 V	0.00001
Electrolytic Ta (wet)	10 μF/100 V	0.038
Electrolytic Ta (dry)	5.6 μF/10 V	0.0026

[a] HV: High voltage, LV: low voltage.

From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 296. Originally from Badian, L., *Handbuch der Electronik.,* Franzis-Verlag, Munich, Vol. 3, 1979.

Capacitors

Capacitor Name	υ' cm^3/μF	Class	*delta*$_{max}$ after 1000 h [%]	Smallest $t\,\delta_p$ [%]	Power Factor $\times 10^{-4}$	TCC ppm/K	Maximum Work Temperature [°C]	Remarks	
Polystyrene	300	1	0.5	±0.5	2–5	–100	70	For telecommunications filter	Neutral polymer
Teflon	300	1	0.5	±0.5	6	–150	280	Special applications	
Polyethylene	200	1	1	±1	5	–500	100		
Polypropylene	50	2	5	±5	6–8	–200	110		
Metalized polypropylene	10	2	5	±0.5	6–8	–200	85		
Metalized Polyester	5.6	2	10	±10	50 (200 at 1 MHz)	—	—	For ac pulse	Polar polymer
Polyester (polyethylene tereftalate)	12	2	5	±10	50 (200 at 1 MHz)	Large	150		
Polycarbonate	12	2	10	±10	20	Large	100		
Metalized polycarbonate	5.6	2	10	±10	20	Large	100		

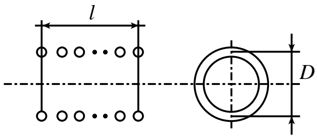
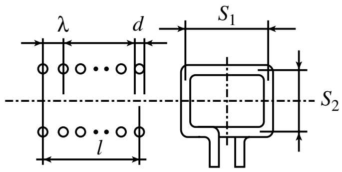
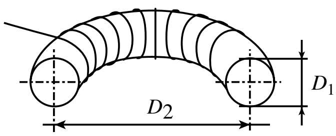
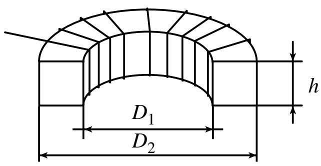
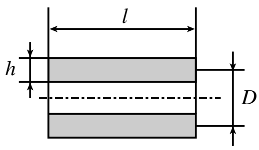
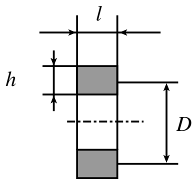
From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 306.

Inductor Qualifiers and Attributes

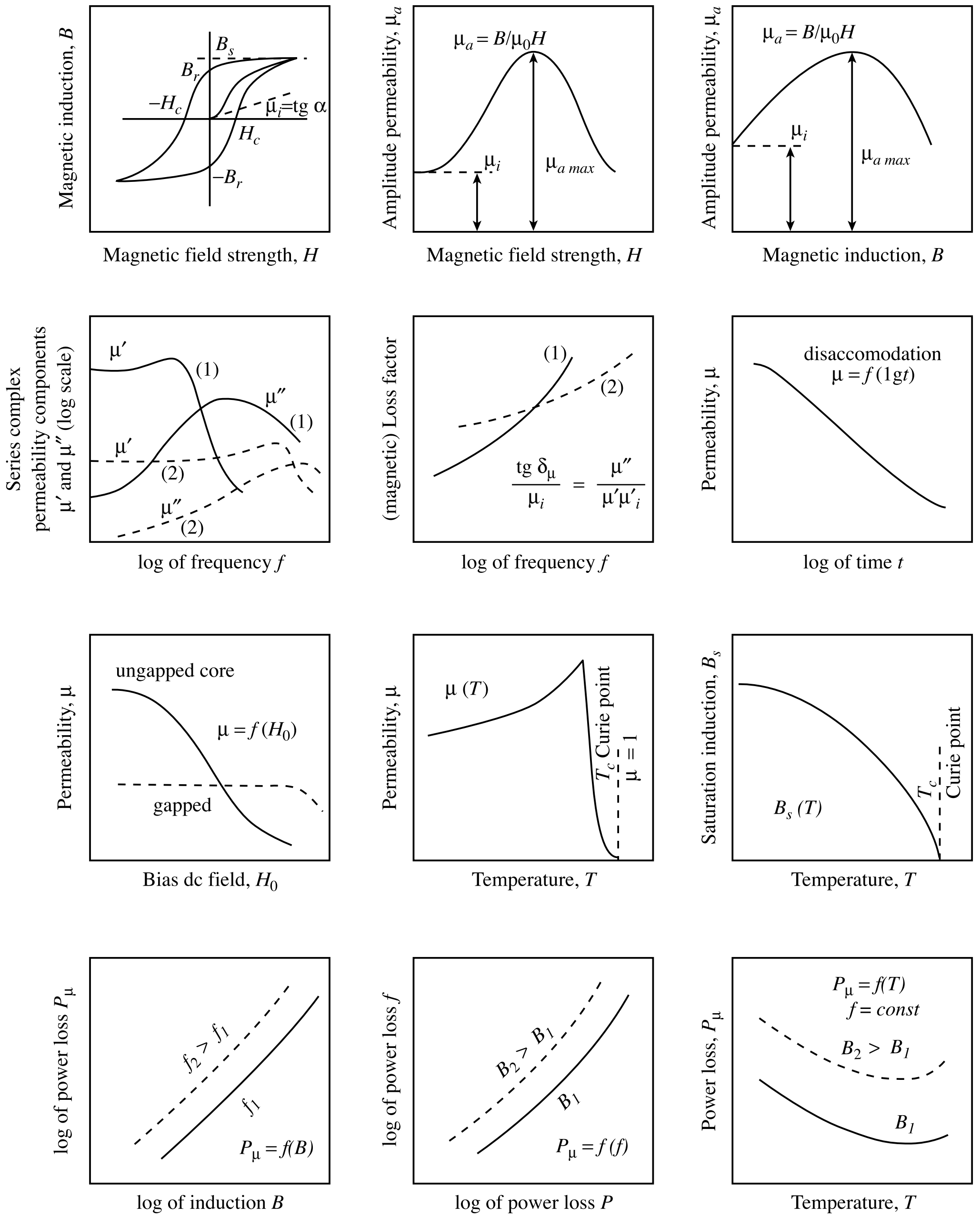
Inductor Qualifier	Inductor: Attribute or Quality
Ideal, perfect	Linear inductor having only a "pure" inductance, i.e., no power loss is related to the flow of time-varying current through the inductor winding. In the ideal inductor, the current of sine wave lags the induced voltage by angle $\varphi = 90°$ ($\pi/2$ rad). The concept of the ideal inductor is used only in idealized or simplified circuit analysis.
Nonideal	Usually, a linear inductor in which the power loss in the winding and core is taken into account. The current of sine wave lags the induced voltage by angle $0° \leq \varphi < 90°$ (90° for ideal, power lossfree inductor; 0° for pure resistor). The concept of nonideal inductor is used as a first order approximation of a real inductor.
Linear	Inductor, ideal or nonideal, for which the induced voltage drop across it is proportional to the flowing time-varying current in its steady state. Linear inductor can be described or be used to describe the circuit in terms of transfer function. An air inductor is an example of linear inductor.
Nonlinear	Inductor for which the induced voltage drop is not proportional to the time-varying current flowing by it. As a rule, cored inductors (specifically if a core forms a closed magnetic circuit) are nonlinear. This is a consequence of the strong nonlinear dependence of magnetic induction B, proportional to voltage $u = dL/dt$, on magnetic field strength H, proportional to current i.
Real	Inductor with electrically behavioral aspects and characteristics that are all taken into account, e.g., magnetic power loss, magnetic flux leakage, self-winding and interwinding capacitances and related dielectric power loss, radiation power loss, parasitic couplings, and so on, and dependences of these factors on frequency, induction, temperature, time, etc.
Air	Inductor not containing magnetic materials as constituents or in its magnetically perceptible vicinity
Cored	Inductor in which a magnetic material in the form of a core serves intentionally as a path, complete or partial, for guidance of magnetic flux generated by current flowing through inductor winding
Lumped or discrete	Inductor assumed to be concentrated at a single point
Distributed	Inductor with inductance and other properties that are distributed over a physical distance(s) which is(are) comparable to a wavelength

From Nowak, S., Capacitor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 314.

Inductance L_0 of Various Air Inductors Dimensionally Similar but Having the Same Number of Turns

	Winding (Coil) Dimensions	When Coil Dimensions Are:	Inductance L_0 for n=100 Turns Is:
(a)		$D_1 = 2$ cm $l = 10$ cm	19 μH
(b)		$S_1 = 1.5$ cm $S_2 = 2.5$ cm $\lambda = 0.05$ cm $l = 10$ cm $d = 0.05$ cm $G\,(0.6;4) = 0.4$ $H\,(1;100) = 0$	32 μH
(c)		$D_1 = 1$ cm $D_2 = 3$ cm	10.3 μH
		$D_1 = 2$ cm $D_2 = 3$ cm	41 μH
(d)		$D_1 = 2$ cm $D_2 = 4$ cm $h = 1$ cm	13.9 μH
		$D_1 = 1$ cm $D_2 = 5$ cm $h = 2$ cm	64.4 μH
(e)		$D = 2$ cm $h = 0.5$ cm $l = 4$ cm	74 μH
(f)		$D = 2$ cm $h = 0.5$ cm $l = 0.2$ cm	245 μH

From Postupolski, T.W., Inductor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 316.

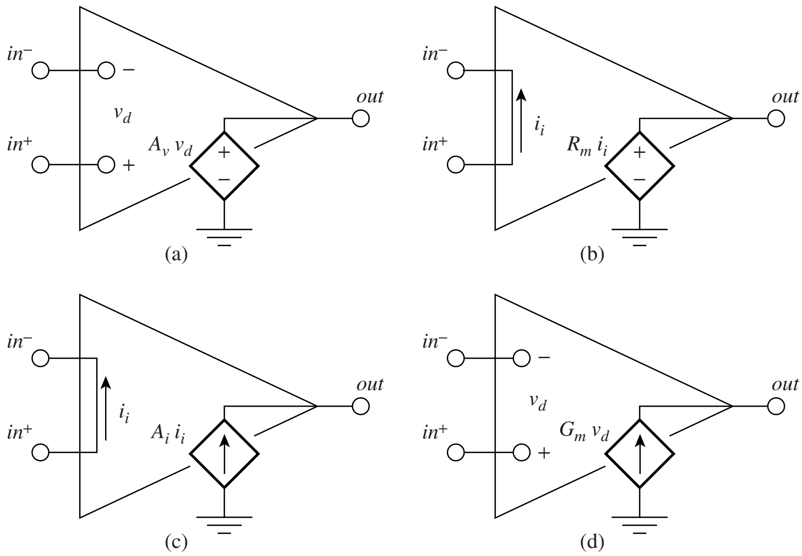


Basic characteristics of magnetic materials essential for inductor applications. (From Postupolski, T.W., Inductor, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 331.)

Ideal Op Amp Types

Input	Output	Gain	Type
V	V	A_v	Voltage
I	V	R_m	Transimpedance
I	I	A_i	Current
V	I	G_m	Transconductance

From Nairn, D.G., The ideal operational amplifier, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 428.



The four possible op amp configurations: (a) the voltage op amp, (b) the transimpedance op amp, (c) the current op amp, and (d) the transconductance op amp. (From Nairn, D.G., The ideal operational amplifier, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 428.)

ITRS Microprocessor Roadmap

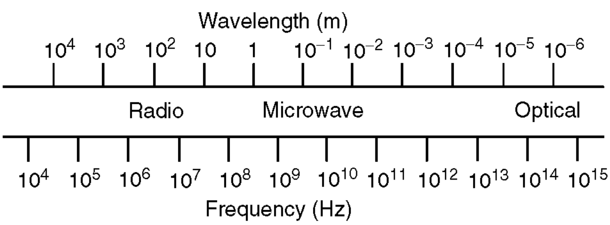
Characteristic	2001	2004	2007	2010	2013	2016
Transistor gate length (nm)	90	53	35	25	18	13
Feature size scale factor ($S_{feature}$)	1	0.59	0.39	0.28	0.20	0.14
Chip size (mm^2)	310	310	310	310	310	310
Million transistors/mm^2	0.89	1.78	3.1	7.14	14.27	28.54
Million transistors/chip	275.9	551.8	961	2213.4	4423.7	8847.4
Clock frequency (GHz)	1.684	3.99	6.739	11.511	19.348	28.751
Supply voltage (V)	1.1	1	0.7	0.6	0.5	0.4
Maximum power (W)	130	160	190	218	251	288

From Cottrell, D., Design automation technology roadmap, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 2161.

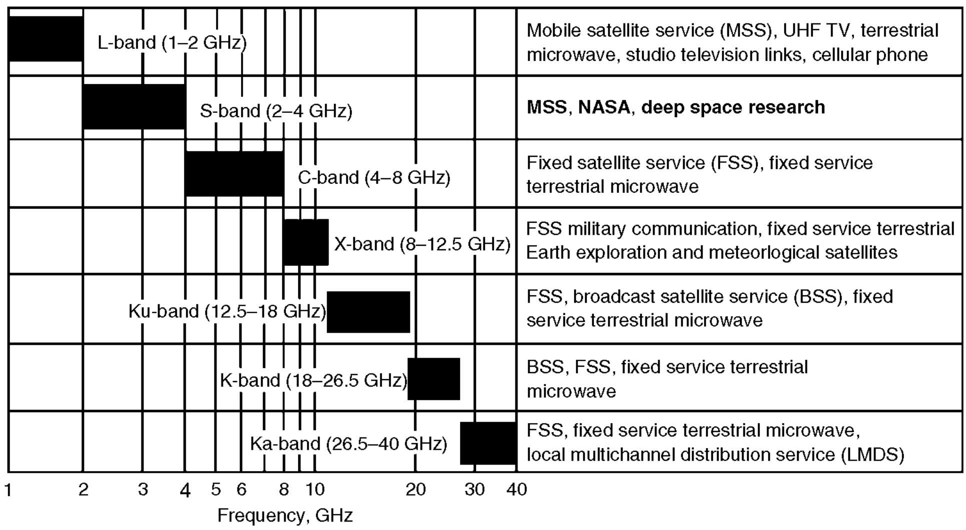
Properties of the Relative Sensitivity

Property Number	Relation	Property Number	Relation
1	$S_x^{ky} = S_{kx}^{y} = S_x^y$	10	$S_x^{y_1/y_2} = S_x^{y_1} - S_x^{y_2}$
2	$S_x^x = S_x^{kx} = S_{kx}^x = 1$	11	$S_{x_1}^y = S_{x_2}^y S_{x_1}^{x_2}$
3	$S_{1/x}^y = S_x^{1/y} = -S_x^y$	12[a]	$S_x^y = S_x^{\lvert y \rvert} + j \arg y S_x^{\arg y}$
4	$S_x^{y_1 y_2} = S_x^{y_1} + S_x^{y_2}$	13[a]	$S_x^{\arg y} = \frac{1}{\arg y} \operatorname{Im} S_x^y$
5	$S_x^{\Pi_{i=1}^n y_i} = \sum_{i=1}^{n} S_x^{y_i}$	14[a]	$S_x^{\lvert y \rvert} = \operatorname{Re} S_x^y$
6	$S_x^{y^n} = n S_x^y$	15	$S_x^{y+z} = \frac{1}{y+z}\left(y S_x^y + z S_x^z\right)$
7	$S_x^{x^n} = n S_x^{kx^n} = n$	16	$S_x^{\Sigma_{i=1}^n y_i} = \frac{\sum_{i=1}^{n} y_i S_x^{y_i}}{\sum_{i=1}^{n} y_i}$
8	$S_{x^n}^y = \frac{1}{n} S_x^y$	17	$S_x^{\ln y} = \frac{1}{\ln y} S_x^y$
9	$S_{x^n}^x = S_{kx^n}^x = \frac{1}{n}$		

[a] In this relation, y is a complex quantity and x is a real quantity.
From Filanovsky, I., Sensitivity and selectivity, in *The Circuits and Filters Handbook,* 2nd ed., Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2003, p. 2294.



Portion of the electromagnetic spectrum. (From Palais, J., Fiber optic communications systems, in *The Communications Handbook,* 2nd ed., Gibson, J.D., Ed., CRC Press, Boca Raton, FL, 2002, p. **44**-2.)



The general arrangement of the frequency spectrum that is applied to satellite communications and other radiocommunications services. Indicated are the short-hand letter designations along with an explanation of the typical applications. Note that the frequency ranges indicated are the general ranges and do not correspond exactly to the ITU frequency allocations and allotments. (From Elbert, B.R., Geostationary communications satellites and applications, in *The Communications Handbook,* 2nd ed., Gibson, J.D., Ed., CRC Press, Boca Raton, FL, 2002, p. **56**-5.)

The Primary Strengths of Satellite Communications

Feature of Satellite Service	Application
Wide-area coverage	Domestic, regional, global
Wide bandwidth	Up to 1 GHz per coverage
Independent of land-based networks	Does not require connection to terrestrial infrastructure
Rapid installation	Individual sites can be installed and activated in one day for VSAT or two months of major hub
Low cost per added site	Depends on type of service; can be as low as $600 for DTH
Uniform service characteristics	Determined by coverage and type of transmission system
Total service from a single provider	By the satellite operator or a separate organization that leases transponder capacity
Mobile Communication	Requires line-of-sight path over the coverage area

From Elbert, B.R., Geostationary communications satellites and applications, in *The Communications Handbook,* 2nd ed., Gibson, J.D., Ed., CRC Press, Boca Raton, FL, 2002, p. **56**-7.

Access time The total time needed to retrieve data from memory. For a disk drive this is the sum of the time to position the read/write head over the desired track and the time until the desired data rotates under the head.

Active filter A form of power electronic converter designed to effectively cancel harmonic currents by injecting currents that are equal and opposite to, or 180° out of phase with, the target harmonics. Active filters allow the output current to be controlled and provide stable operation against AC source impedance variations without interfering with the system impedance.

The main type of active filter is the series type in which a voltage is added in series with an existing bus voltage. The other type is the parallel type in which a current is injected into the bus and cancels the line current harmonics.

Algorithm A systematic and precise, step-by-step procedure (such as a recipe, a program, or set of programs) for solving a certain kind of problem or accomplishing a task, for instance converting a particular kind of input data to a particular kind of output data, or controlling a machine tool. An algorithm can be executed by a machine.

Address A unique identifier for the place where information is stored (as opposed to the contents actually stored there). Most storage devices may be regarded by the user as a linear array, such as bytes or words in RAM or sectors on a disk. The address is then just an ordinal number of the physical or logical position. In some disks, the address may be compound, consisting of the cylinder or track and the sector within that cylinder.

In more complex systems, the address may be a "name" that is more relevant to the user but must be translated by the underlying software or hardware.

Antenna A device used to couple energy from a guiding structure (transmission line, waveguide, etc.) into a propagation medium, such as free space, and vice versa. It provides directivity and gain for the transmission and reception of electromagnetic waves.

Appropriate technology The technology that will accomplish a task adequately given the resources available. Adequacy can be verified by determining that increasing the technological content of the solution results in diminishing gains or increasing costs.

Attenuation The exponential decrease, with distance, in the amplitude of an electric signal traveling along a very long transmission line due to losses in the supporting medium. In electromagnetic systems attenuation is due to conductor and dielectric losses. In fiber optic systems attenuation arises from intrinsic material properties (absorption and Rayleigh scattering) and from waveguide properties such as bending, microbending, splices, and connectors.

Automation Refers to the bringing together of machine tools, materials handling process, and controls with little worker intervention, including

1. a continuous flow production process that integrates various mechanisms to produce an item with relatively few or no worker operations, usually through electronic control;
2. self-regulating machines (feedback) that can perform highly precise operations in sequence; and
3. electronic computing machines.

In common use, however, the term is often used in reference to any type of advanced mechanization or as a synonym for technological progress; more specifically, it is usually associated with cybernetics.

Base (1) The number of digits in a number system (10 for decimal, 2 for binary).

(2) One of the three terminals of a bipolar transistor.

(3) A register's value that is added to an immediate value or to the value in an index register in order to form the effective address for an instruction such as LOAD or STORE.

Bayesian theory Theory based on Bayes' rule, which allows one to relate the *a priori* and *a posteriori* probabilities. If $P(c_i)$ is the *a priori* probability that a pattern belongs to class c_i, $P(\mathbf{x_k})$ is the probability of pattern $\mathbf{x_k}$, $P(\mathbf{x_k}|c_i)$ is the class conditional probability that the pattern is $\mathbf{x_k}$ provided that it belongs to class c_i, $P(c_i|\mathbf{x_k})$ is the *a posteriori* conditional probability that the given pattern class membership is c_i, given pattern $\mathbf{x_k}$, then

$$P(c_i|\mathbf{x_k}) = \frac{P(\mathbf{x_k}|c_i)P(c_i)}{P(\mathbf{x_k})}$$

The membership of the given pattern is determined by

$$\max_{c_i} P(c_i|\mathbf{x_k}) = \max_{c_i} P(\mathbf{x_k}|c_i)P(c_i)$$

Hence, the *a posteriori* probability can be determined as a function of the *a priori* probability.

Binary-coded decimal (BCD) A weighted code using patterns of four bits to represent each decimal position of a number.

Bit (1) The fundamental unit of information representation in a computer, short for "binary digit" and with two values usually represented by "0" and "1." Bits are usually aggregated into "bytes" (7 or 8 bits) or "words" (12–60 bits).

A single bit within a word may represent the coefficient of a power of 2 (in numbers), a logical TRUE/FALSE quantity (masks and Boolean quantities), or part of a character or other compound quantity. In practice, these uses are often confused and interchanged.

(2) In Information Theory, the unit of information. If an event E occurs with a probability $P(E)$, it conveys information of $\log_2 (1/P(E))$ binary units or bits. When a bit (binary digit) has equiprobable 0 and 1 values, it conveys exactly 1.0 bit (binary unit) of information; the average information is usually less than this.

Boundary condition (1) The conditions satisfied by a function at the boundary of its interval of definition. They are generally distinguished in hard or soft also called Neumann (the normal derivative of the function is equal to zero) or Dirichlet (the function itself is equal to zero).

(2) The conditions satisfied from the electromagnetic field at the boundary between two different media.

(3) Rules that govern the behavior of electromagnetic fields as they move from one medium into another medium.

Broadcasting Sending a message to multiple receivers.

Bus (1) A data path connecting the different subsystems or modules within a computer system. A computer system will usually have more than one bus; each bus will be customized to fit the data transfer needs between the modules that it connects.

(2) A conducting system or supply point, usually of large capacity. May be composed of one or more conductors, which may be wires, cables, or metal bars (busbars).

(3) A node in a power system problem.

(4) A heavy conductor, typically used with generating and substation equipment.

Byte In most computers, the unit of memory addressing and the smallest quantity directly manipulated by instructions. The term *byte* is of doubtful origin, but was used in some early computers to denote any field within a word (e.g., DEC PDP-10). Since its use on the IBM "Stretch" computer (IBM 7030) and especially the IBM System/360 in the early 1960s, a byte is now generally understood to be 8 bits, although 7 bits is also a possibility.

Cache An intermediate memory store having storage capacity and access times somewhere in between the general register set and main memory. The cache is usually invisible to the programmer, and its effectiveness comes from being able to exploit program locality to anticipate memory-access patterns and to hold closer to the CPU: most accesses to main memory can be satisfied by the cache, thus making main memory appear to be faster than it actually is.

A hit occurs when a reference can be satisfied by the cache; otherwise a miss occurs. The proportion of hits (relative to the total number of memory accesses) is the hit ratio of the cache.

Capacitance The measure of the electrical size of a capacitor, in units of farads. Thus a capacitor with a large capacitance stores more electrons (coulombs of charge) at a given voltage than one with a smaller capacitance.

In a multiconductor system separated by nonconductive mediums, capacitance (C) is the proportionality constant between the charge (q) on each conductor and the voltage (V) between each conductor. The total equilibrium system charge is zero. Capacitance is dependent on conductor geometry, conductor spatial relationships, and the material properties surrounding the conductors.

Capacitors are constructed as two metal surfaces separated by a nonconducting electrolytic material. When a voltage is applied to the capacitor, the electrical charge accumulates in the metals on either side of the nonconducting material, negative charge on one side and positive on the other. If this material is a fluid then the capacitor is electrolytic; otherwise, it is nonelectrolytic.

Causal system A system whose output does not depend on future input; the output at time t may depend only on the input signal $\{f(\tau) : \tau \leq t\}$. For example, the voltage measured across a particular element in a passive electric circuit does not depend upon future inputs applied to the circuit and hence is a causal system.

If a system is not causal, then it is noncausal. An ideal filter which will filter in real time all frequencies present in a signal $f(t)$ requires knowledge of $\{f(\tau) : \tau > t\}$ and is an example of a noncausal system.

Central processing unit (CPU) A part of a computer that performs the actual data processing operations and controls the whole computing system. It is subdivided into two major parts:

1. The arithmetic and logic unit (ALU), which performs all arithmetic, logic, and other processing operations.
2. The control unit (CU), which sequences the order of execution of instructions, fetches the instructions from memory, decodes the instructions, and issues control signals to all other parts of the computing system. These control signals activate the operations performed by the system.

Channel (1) The medium along which data travel between the transmitter and receiver in a communication system. This could be a wire, coaxial cable, free space, etc.

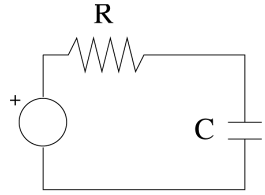
(2) The conductivity path between the source and the drain of a field effect transistor.

(3) A single path for transmitting electrical signals. Example 1: The band of frequencies from 50 Hz to 15 KHz (Channel A) and 15 KHz to 75 KHz (Channel B) which frequency modulates the main carrier of an FM stereo transmitter. Example 2: A portion of the electromagnetic spectrum assigned for operation of a specific carrier from the FM broadcast band (88 to 108 MHz) of frequencies 200 KHz wide designated by the center frequency beginning at 88.1 MHz and continuing in successive steps to 107.9 MHz.

Chaos (1) Erratic and unpredictable dynamic behavior of a deterministic system that never repeats itself. Necessary conditions for a system to exhibit such behavior are that it be nonlinear and have at least three independent dynamic variables.

(2) In microelectronics, deterministic motion, in which the statistics are essentially those of a Gaussian random process.

Circuit A physical device consisting of an interconnection of elements, or a topological model of such a device. For example, an electric circuit may be constructed by interconnecting a resistor and a capacitor to a voltage source. A representation of this circuit is shown by the diagram in the figure.



Circuit example.

Code (1) A technique for representing information in a form suitable for storage or transmission.

(2) A mapping from a set of messages into binary strings.

Computer (1) An electronic, electromechanical, or purely mechanical device that accepts input, performs some computational operations on the input, and produces some output.

(2) Functional unit that can perform substantial computations, including numerous arithmetic operations, or logic operations, without human intervention during a run.

(3) General or special-purpose programmable system that is able to execute programs automatically. It has one or more associated processing units, memory, and peripheral equipment for input and output. Uses internal memory for storing programs and/or data.

Conductivity (1) The reciprocal of resistivity.

(2) A measure of a material's ability to conduct electrical current. Conductivity σ is the ratio of the conduction current to the electric field in Ohm's Law:

$$J_c = \sigma E$$

Dielectric (1) A medium that exhibits negligible or no electrical conductivity and thus acts as a good electrical insulator.

(2) A medium characterized by zero conductivity, unity relative permeability, and a relative permittivity greater than one. Also known as an insulator.

Dielectries are usually used to separate two conducting bodies such as to form a capacitor.

Electric field In a region of space, if a test charge q experiences a force F, then the region is said to be characterized by an electric field of intensity E given by

$$E = \frac{F}{q}$$

Electromagnetic energy Energy contained in electromagnetic fields and associated polarizable and magnetizable media.

Ethernet A standard for interconnecting devices on a local area network (LAN).

Gate (1) A logical or physical entity that performs one logical operation, such as AND, NOT, or OR.

(2) The terminal of a FET which controls the flow of electrons from source to drain. It is usually considered to be the metal contact at the surface of the die. The gate is usually so thin and narrow that if any appreciable current is allowed to flow, it will rapidly heat up and self-destruct due to I-R loss. This same resistance is a continuing problem in low noise devices and has resulted in the creation of numerous methods to alter the gate structure and reduce this effect.

Ground (1) An earth-connected electrical conducting connection that may be designed or nonintentionally created.

(2) The electrical "zero" state, used as the reference voltage in computer systems.

Hologram Medium that when illuminated optically, provides a three-dimensional image of stored information, sometimes called holograph.

Laser Acronym that stands for light amplification by stimulated emission of radiation. Usually refers to an oscillator rather than an amplifier; commonly also refers to similar systems that operate at non-optical frequencies or with nonelectromagnetic wave fields.

Node A symbol representing a physical connection between two electrical components in a circuit.

Noise (1) Any undesired disturbance, whether originating from the transmission medium or the electronics of the receiver itself, that gets superimposed onto the original transmitted signal by the time it reaches the receiver. These disturbances tend to interfere with the information content of the original signal and will usually define the minimum detectable signal level of the receiver.

(2) Any undesired disturbance superimposed onto the original input signal of an electronic device; noise is generally categorized as being either external (disturbances superimposed onto the signal before it reaches the device) or internal (disturbances added to the signal by the receiving device itself). Some common examples of external noise are crosstalk and impulse noise as a result of atmospheric disturbances or manmade electrical devices. Some examples of internal noise include thermal noise, shot noise, l/f noise, and intermodulation distortion.

Permeability Tensor relationship between the magnetic field vector and the magnetic flux density vector in a medium with no hysteresis; flux density divided by the magnetic field in scalar media. Permeability indicates the ease with which a magnetic material can be magnetized. An electromagnet with a higher permeable core material will produce a stronger magnetic field than one with a lower permeable core material. Permeability is analogous to conductance when describing electron flow through a material.

Port (1) A terminal pair.

(2) A place of connection between one electronic device and another.

(3) A point in a computer system where external devices can be connected.

Random signal A signal $X(t)$ that is either noise $N(t)$, an interfering signal $s(t)$, or a sum of these:

$$X(t) = s_1(t) + \cdots + s_m(t) + N_1(t) + \cdots + N_n(t)$$

Resolution (1) The act of deriving from a sound, scene, or other form of intelligence, a series of discrete elements from which the original may subsequently be reconstructed. The degree to which nearly equal values of a quantity can be discriminated.

(2) The fineness of detail in a measurement. For continuous systems, the minimum increment that can be discerned.

(3) The ability to distinguish between two units of measurement.

(4) The number of pixels per linear unit (or per dimension) in a digital image.

(5) The smallest feature of a given type that can be printed with acceptable quality and control.

Sensor A transducer or other device whose input is a physical phenomenon and whose output is a quantitative measurement of that physical phenomenon. Physical phenomena that are typically measured by a sensor include temperature or pressure to an internal, measurable value such as voltage or current.

Traveling wave An electromagnetic signal that propagates energy through space or a dielectric material.

Waveguide A system of conductive or dielectric materials in which boundaries and related dimensions are defined such that electromagnetic waves propagate within the bounded region of the structure. Although most waveguides utilize a hollow or dielectric filled conductive metal tube, a solid dielectric rod in which the dielectric constant of the rod is very much different from the dielectric constant of the surrounding medium can also be used to guide a wave. Waveguides rapidly attenuate energy at frequencies below the waveguide lower cut-off frequency, and are limited in bandwidth at the upper end of the frequency spectrum due to wave attenuation as well as undesired mode propagation.

From *Comprehensive Dictionary of Electrical Engineering*, Laplante, P.A., Ed., CRC Press, Boca Raton, FL, 1999.

Cost of Selected Memory Devices

Year	Device	Size (bits)	Cost ($)	Cost ($/MB)	Speed (ns)
1943	Relay	1	—	—	100,000,000
1958	Magnetic drum (IBM650)	80,000	157,400	1.7E+07	4,800,000
1959	Vacuum tube flip-flop	1	8.10	6.8E+07	10,000
1960	Core	8	5.00	5.2E+06	11,500
1964	Transistor flip-flop	1	59.00	4.9E+08	200
1966	I.C. flip-flop	1	6.80	5.7E+07	200
1970	Core	8	0.70	7.3E+05	770
1972	I.C. flip-flop	1	3.30	2.8E+07	170
1975	256 bit static RAM	256	—	—	1,000
1977	1 Kbit static RAM	1,024	1.62	1.3E+04	500
1977	4 Kbit DRAM	4,096	16.40	3.4E+04	270
1979	16 Kbit DRAM	16,384	9.95	5.1E+03	350
1982	64 Kbit DRAM	65,536	6.85	8.8E+02	200
1985	256 Kbit DRAM	262,144	6.00	1.9E+02	200
1989	1 Mbit DRAM	1,048,576	20.00	1.6E+02	120
1991	4 M x 9 DRAM SIMM	37,748,736	165.00	3.7E+01	80
1995	16 MB ECC DRAM DIMM	150,994,944	489.00	2.7E+01	70
1999	64 MB PC-100 DIMM	536,870,912	55.00	8.6E–01	60/10
2001	256 MB PC-133 DIMM	2,147,483,648	88.00	3.4E–01	45/7
2002	1 Gbit chip	1,073,741,824	—	—	—
2005	4 Gbit chip	4,294,967,296	—	—	—

From McCallum, J.C., Price-performance of computer technology, in *The Computer Engineering Handbook,* Oklobdzija, V.G., Ed., CRC Press, Boca Raton, FL, 2002, p. **4**-10.

4-Bit Fractional Two's Complement Numbers

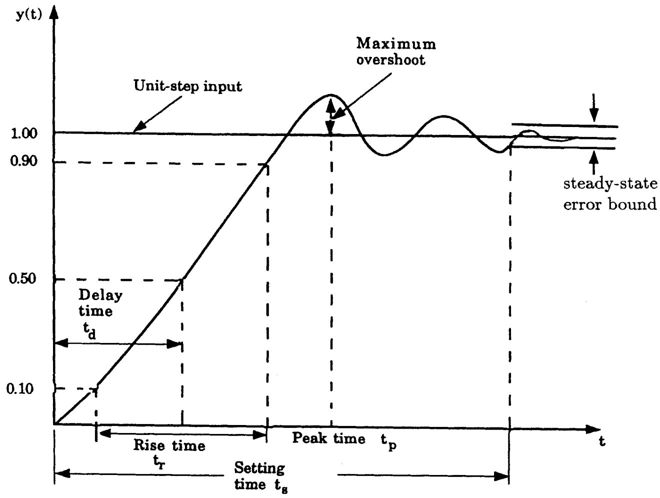
Decimal Fraction	Binary Representation
+7/8	0111
+3/4	0110
+5/8	0101
+1/2	0100
+3/8	0011
+1/4	0010
+1/8	0001
+0	0000
−1/8	1111
−1/4	1110
−3/8	1101
−1/2	1100
−5/8	1011
−3/4	1010
−7/8	1001
−1	1000

From Swartzlander, E.E. Jr., High-speed computer arithmetic, in *The Computer Engineering Handbook,* Oklobdzija, V.G., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-2.

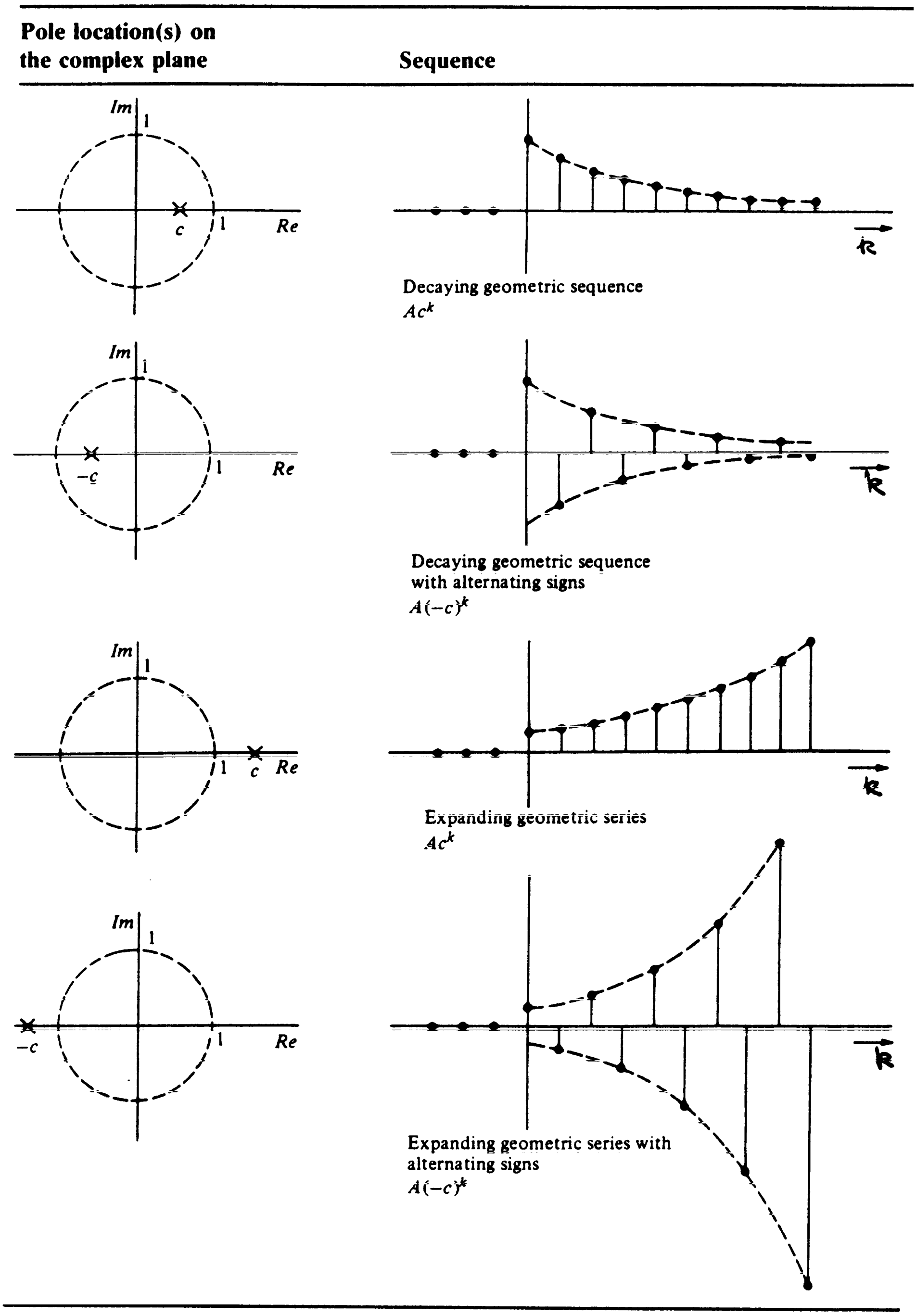
DFT Parameters

DFT Parameter	Notation or Units
Sample size	N samples
Sample period	T_s seconds
Record length	$T = NT_s$ seconds
Number of harmonics	N harmonics
Number of positive (negative) harmonics	$N/2$ harmonics
Frequency spacing between harmonics	$\Delta f = 1/T = 1/NT_s = f_s/N$ Hz
DFT frequency (one-sided baseband range)	$f \in [0, f_s/2)$ Hz
DFT frequency (two-sided baseband range)	$f \in [-f_s/2, f_s/2)$ Hz
Frequency of the *k*th harmonic	$f_k = kf_s/N$ Hz

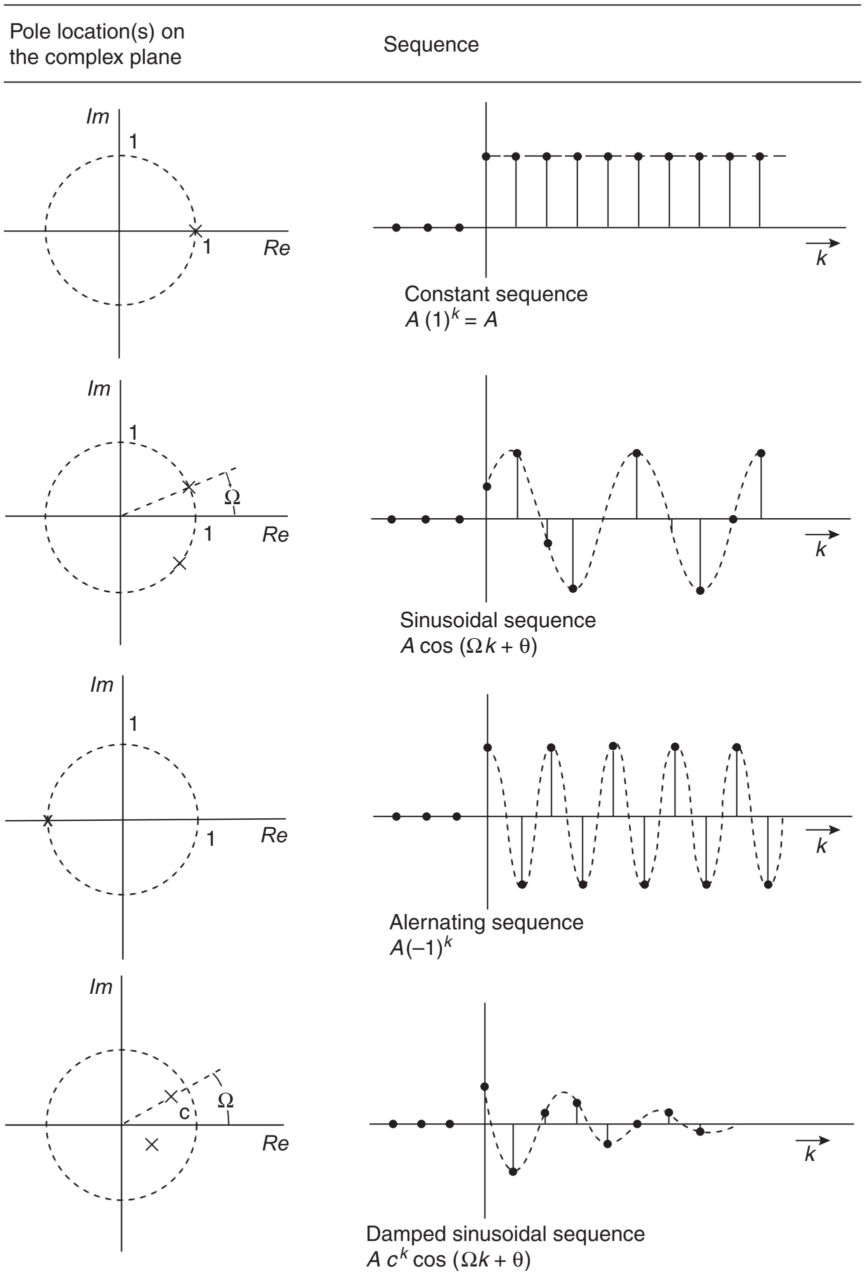
From Taylor, F.J., Digital signal processing, in *The Computer Engineering Handbook,* Oklobdzija, V.G., Ed., CRC Press, Boca Raton, FL, 2002, p. **24**-9.



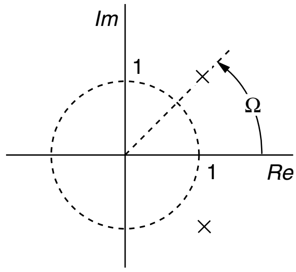
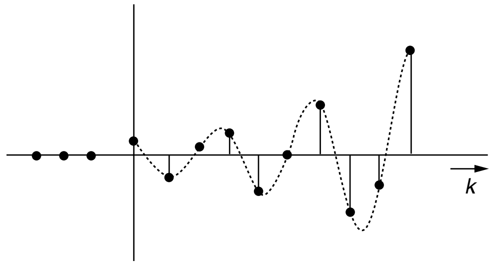
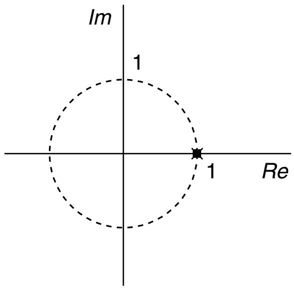
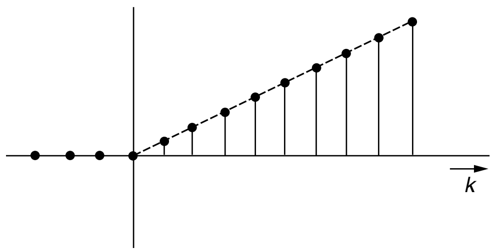
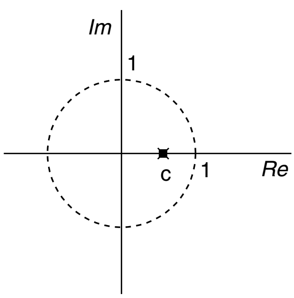
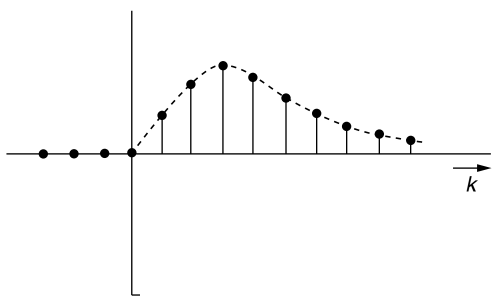
Typical underdamped unit-step response of a control system. An overdamped unit-step response would not have a peak. (From Yang, J.-S. and Levine, W.S., Specification of control systems, in *The Control Handbook,* Levine, W.S., Ed., CRC Press, Boca Raton, FL, 1996, p. 158.)



Sequences corresponding to various z-transform pole locations. (From Santina, M.S., Stubberud, A.R., and Hostetter, G.H., Discrete-time systems, in *The Control Handbook,* Levine, W.S., Ed., CRC Press, Boca Raton, FL, 1996, pp. 243-245.)



(Continued) Sequences corresponding to various *z*-transform pole locations.

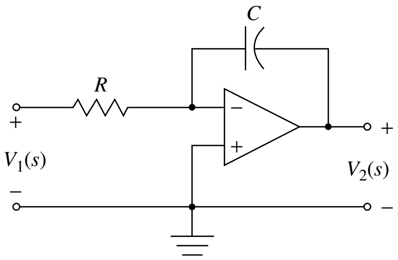
Pole location(s) on the complex plane	Sequence
	 Exponentially expanding sinusoidal sequence $A^k \cos(\Omega k + \theta)$
	 Ramp sequence $Ak(1)^k = Ak$
	 Ramp-weighted geometric sequence Akc^k

(Continued) Sequences corresponding to various *z*-transform pole locations.

Transfer Functions of Dynamic Elements and Networks

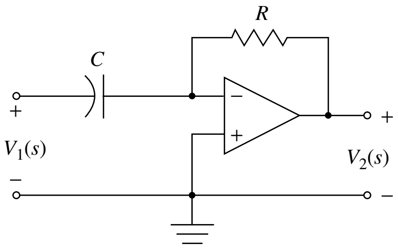
Element or System	G(s)

1. Integrating circuit, filter



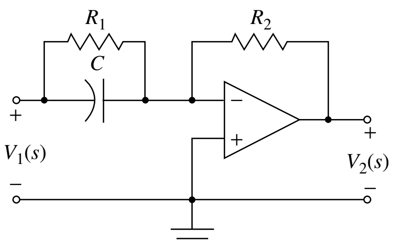
$$\frac{V_2(s)}{V_1(s)} = \frac{1}{RCs}$$

2. Differentiating circuit



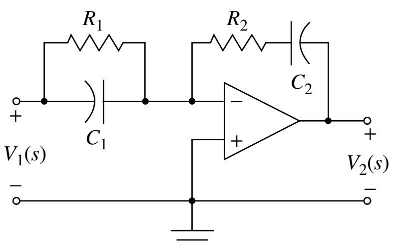
$$\frac{V_2(s)}{V_1(s)} = RCs$$

3. Differentiating circuit



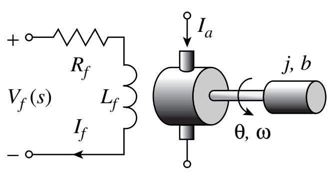
$$\frac{V_2(s)}{V_1(s)} = -\frac{R_2(R_1Cs+1)}{R_1}$$

4. Integrating filter



$$\frac{V_2(s)}{V_1(s)} = -\frac{(R_1C_1s+1)(R_2C_2s+1)}{R_1C_2s}$$

5. dc motor, field-controlled, rotational actuator

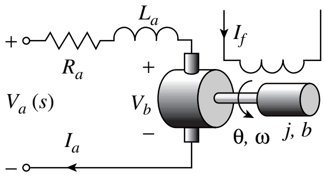


$$\frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js+b)(L_fs+R_f)}$$

Transfer Functions of Dynamic Elements and Networks (continued)

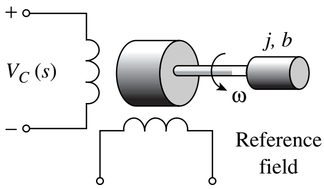
Element or System	G(s)

6. dc motor, armature-controlled, rotational actuator



$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s\left[(R_a + L_a s)(Js + b) + K_b K_m\right]}$$

7. ac motor, two-phase control field, rotational actuator

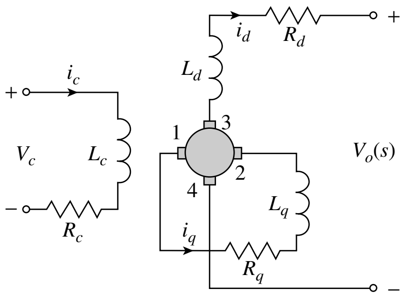


$$\frac{\theta(s)}{V_c(s)} = \frac{K_m}{s(\tau s + 1)}$$

$$\tau = J/(b - m)$$

m = slope of linearized torque-speed curve (normally negative)

8. Amplidyne, voltage and power amplifier

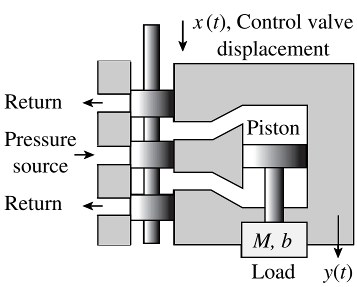


$$\frac{V_o(s)}{V_c(s)} = \frac{(K/R_c R_q)}{(s\tau_c + 1)(s\tau_q + 1)}$$

$$\tau_c = L_c/R_c,\ \tau_q = L_q/R_q$$

For the unloaded case, $i_d \simeq 0$, $\tau_c \simeq \tau_q$,
$0.05\ \text{s} < \tau_c < 0.5\text{s}$
$V_{12} = V_q$, $V_{34} = V_d$

9. Hydraulic actuator



$$\frac{Y(s)}{X(s)} = \frac{K}{s(Ms + B)}$$

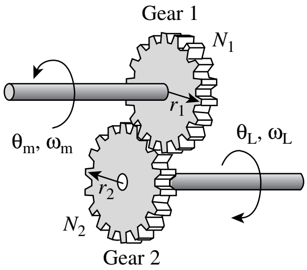
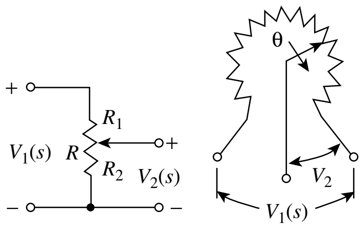
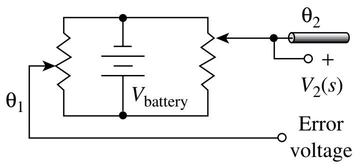
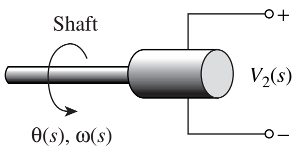
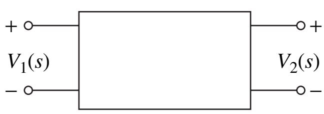
$$K = \frac{Ak_x}{k_p}, \quad B = \left(b + \frac{A^2}{k_p}\right)$$

$$k_x = \left.\frac{\partial g}{\partial x}\right|_{x_0}, \quad k_p = \left.\frac{\partial g}{\partial P}\right|_{P_0},$$

$$g = g(x, P) = \text{flow}$$

$$A = \text{area of piston}$$

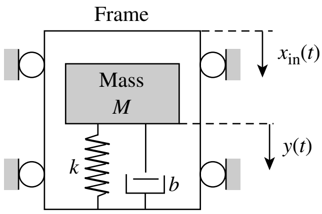
Transfer Functions of Dynamic Elements and Networks (continued)

Element or System	G(s)
10. Gear train, rotational transformer	
	Gear ratio $= n = \dfrac{N_1}{N_2}$ $N_2\theta_L = N_1\theta_m,\ \theta_L = n\theta_m$ $\omega_L = n\omega_m$
11. Potentiometer, voltage control	
	$\dfrac{V_2(s)}{V_1(s)} = \dfrac{R_2}{R} = \dfrac{R_2}{R_1 + R_2}$ $\dfrac{R_2}{R} = \dfrac{\theta}{\theta_{max}}$
12. Potentiometer error detector bridge	
	$V_2(s) = k_s(\theta_1(s) - \theta_2(s))$ $V_2(s) = k_s\theta_{error}(s)$ $k_s = \dfrac{V_{battery}}{\theta_{max}}$
13. Tachometer, velocity sensor	
	$V_2(s) = K_t\omega(s) = K_t s\theta(s)$; K_t = constant
14. dc amplifier	
	$\dfrac{V_2(s)}{V_1(s)} = \dfrac{k_a}{s\tau + 1}$ R_o = output resistance C_o = output capacitance $\tau = R_oC_o$, $\tau \ll 1s$ and is often negligible for controller amplifier

Transfer Functions of Dynamic Elements and Networks (continued)

Element or System	G(s)

15. Accelerometer, acceleration sensor



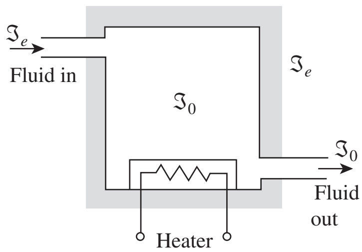
$$x_o(t) = y(t) - x_m(t);$$

$$\frac{X_o(s)}{X_{in}(s)} = \frac{-s^2}{s^2 + (b/M)s + k/M}$$

For low-frequency oscillations, where $\omega < \omega_n$,

$$\frac{X_o(j\omega)}{X_{in}(j\omega)} \simeq \frac{\omega^2}{k/M}$$

16. Thermal heating system



$$\frac{\mathcal{T}(s)}{q(s)} = \frac{1}{C_1 s + (QS + 1/R)}$$, where

$\mathcal{T} = \mathcal{T}_o - \mathcal{T}_e$ = temperature difference due to thermal process

C_t = thermal capacitance

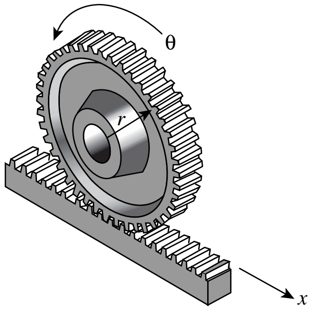
Q = fluid flow rate = constant

S = specific heat of water

R_t = thermal resistance of insulation

$q(s)$ = rate of heat flow of heating element

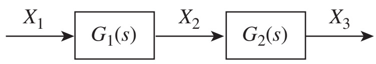
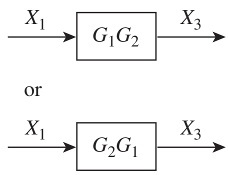
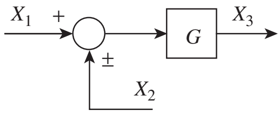
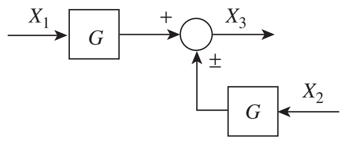
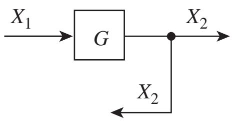
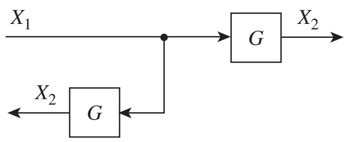
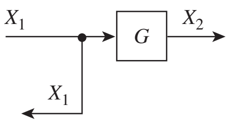
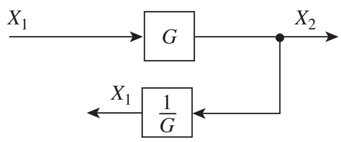
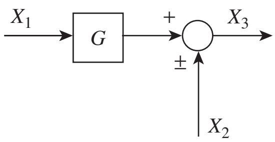
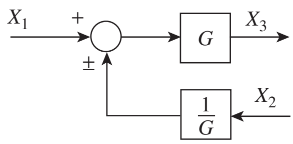
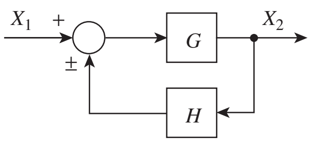
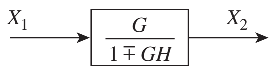
17. Rack and pinion



$x = r\theta$
converts radial motion
to linear motion

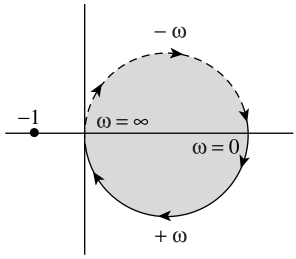
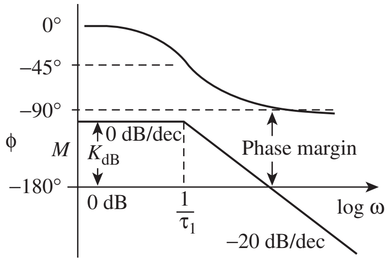
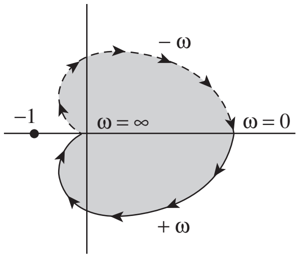
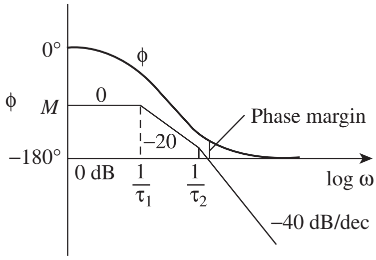
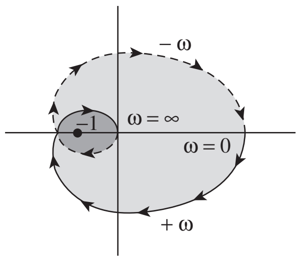
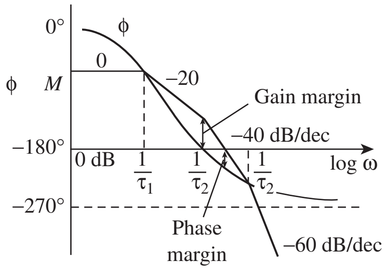
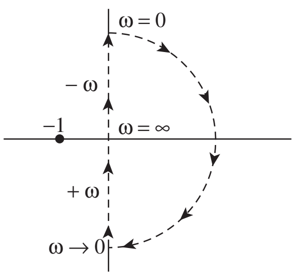
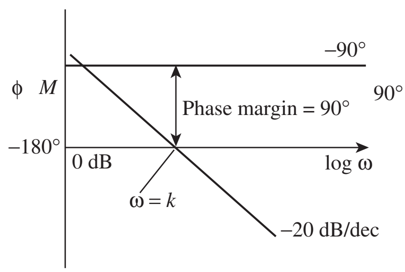
From Dorf, R.C. and Bishop, R.H., Mathematical models of systems, in *Modern Control Systems*, 9th ed., Prentice-Hall, Englewood Cliffs, NJ.

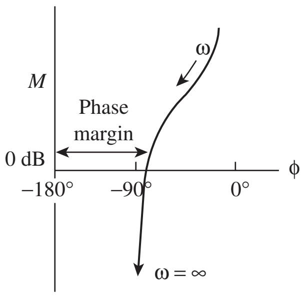
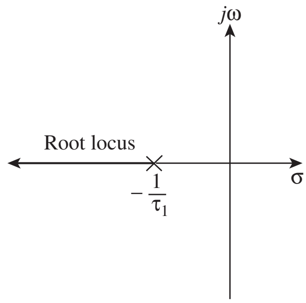
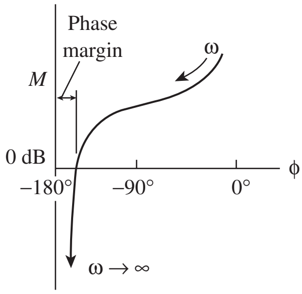
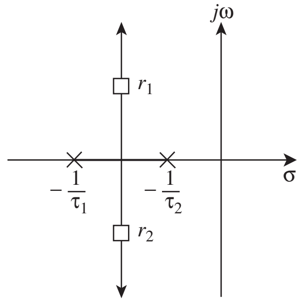
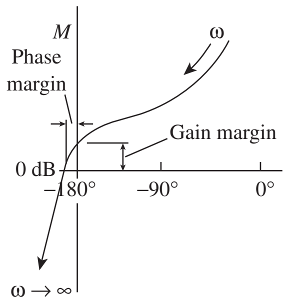
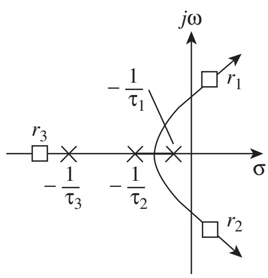
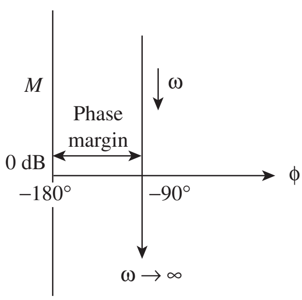
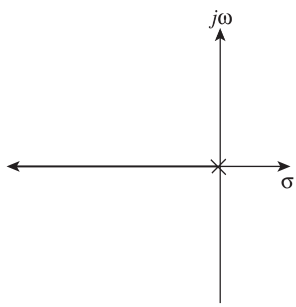
Block Diagram Transformations

Transformation	Original Diagram	Equivalent Diagram
1. Combining blocks in cascade		
2. Moving a summing point behind a block		
3. Moving a pickoff point ahead of a block		
4. Moving a pickoff point behind a block		
5. Moving a summing point ahead of a block		
6. Eliminating a feedback loop		

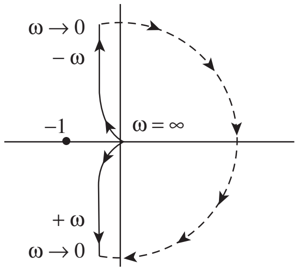
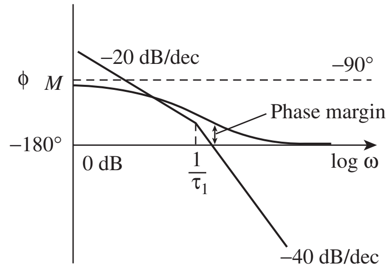
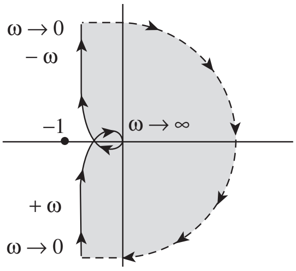
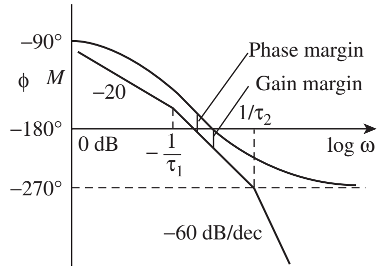
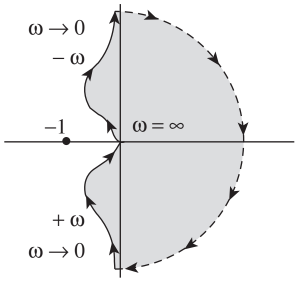
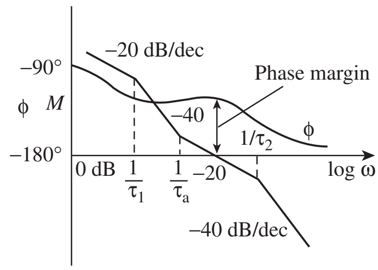
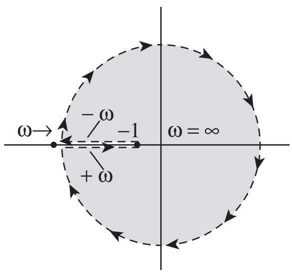
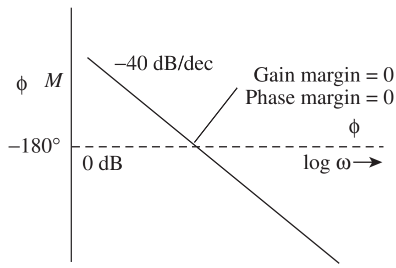
From Dorf, R.C. and Bishop, R.H., Mathematical Models of Systems, in *Modern Control Systems*, 9th ed., Prentice-Hall, Englewood Cliffs, NJ.

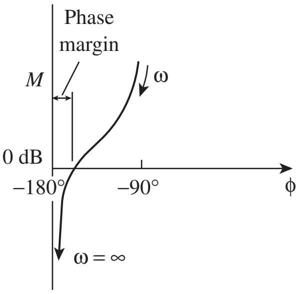
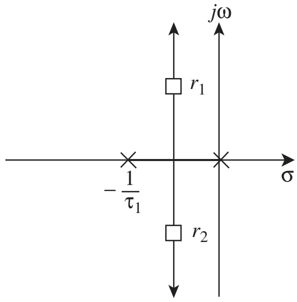
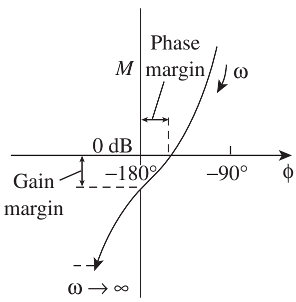
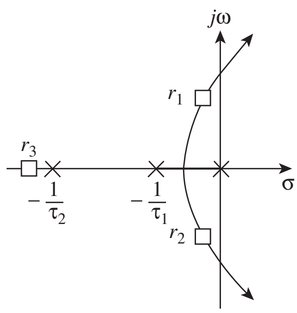
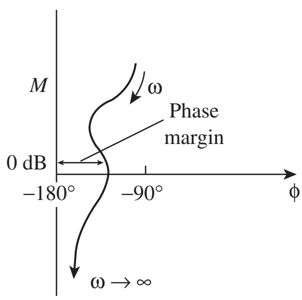
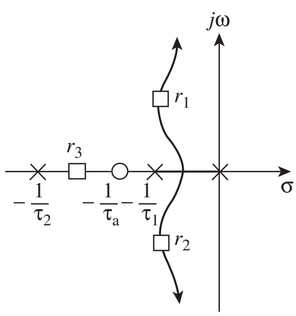
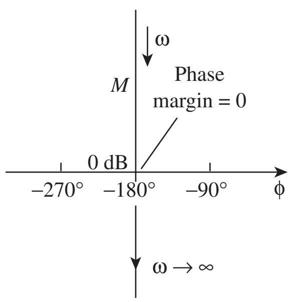
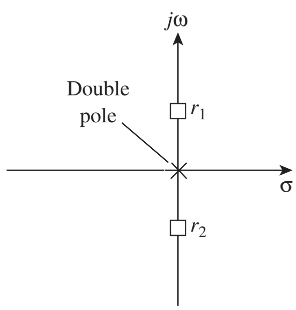
Transfer Function Plots for Typical Transfer Functions

G(s)	Polar Plot	Bode Diagram
1. $\frac{K}{s\tau_1 + 1}$		
2. $\frac{K}{(s\tau_1 + 1)(s\tau_2 + 1)}$		
3. $\frac{K}{(s\tau_1 + 1)(s\tau_2 + 1)(s\tau_3 + 1)}$		
4. $\frac{K}{s}$		

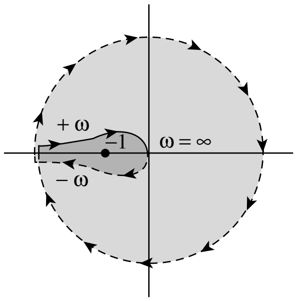
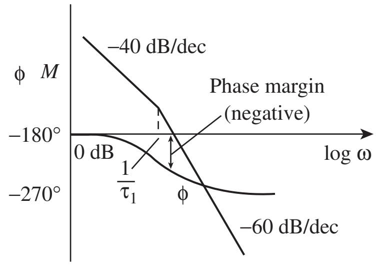
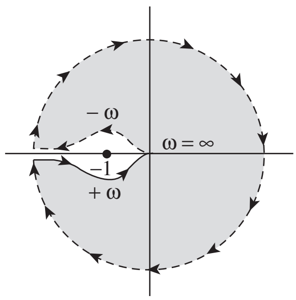
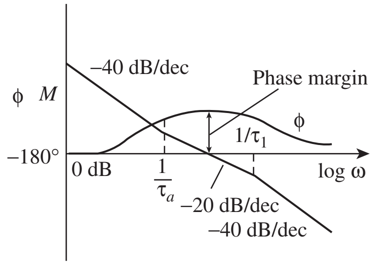
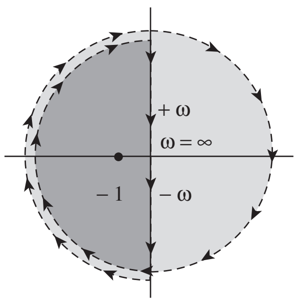
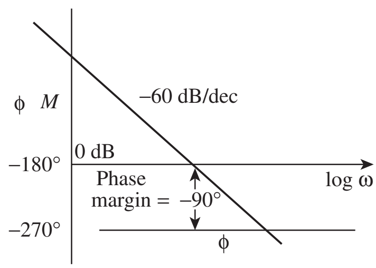
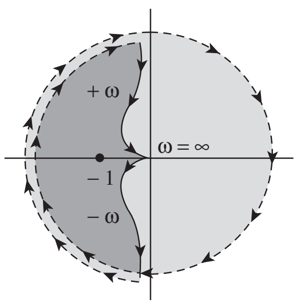
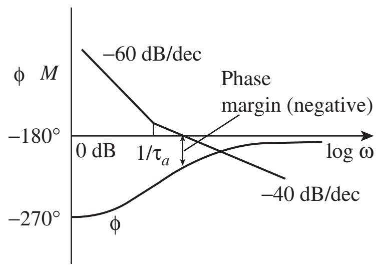
Nichols Diagram	Root Locus	Comments
		Stable; gain margin = ∞
		Elementary regulator; stable; gain margin = ∞
		Regulator with additional energy-storage component; unstable, but can be made stable by reducing gain
		Ideal integrator; stable

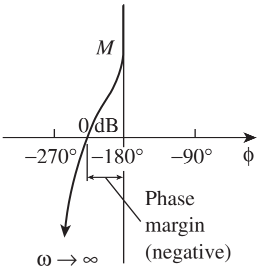
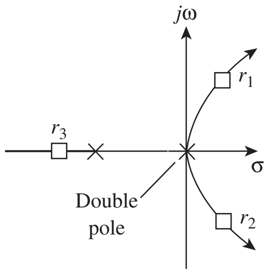
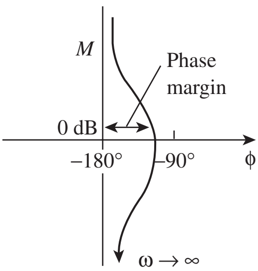
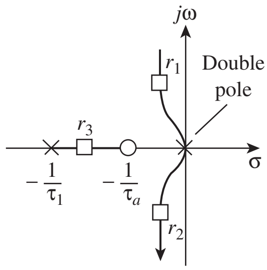
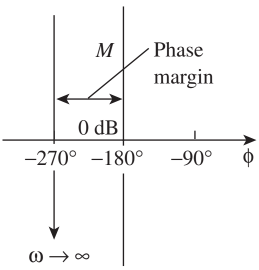
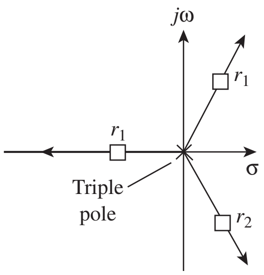
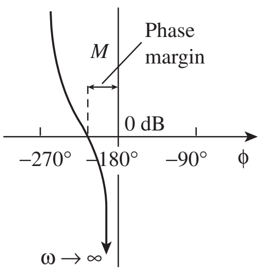
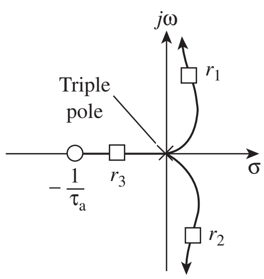
Transfer Function Plots for Typical Transfer Functions (continued)

<table>
<tr><th>G(s)</th><th>Polar Plot</th><th>Bode Diagram</th></tr>
<tr><td>5. $\frac{K}{s(s\tau_1+1)}$</td><td></td><td></td></tr>
<tr><td>6. $\frac{K}{s(s\tau_1+1)(s\tau_2+1)}$</td><td></td><td></td></tr>
<tr><td>7. $\frac{K(s\tau_a+1)}{(s\tau_1+1)(s\tau_2+1)}$</td><td></td><td></td></tr>
<tr><td>8. $\frac{K}{s^2}$</td><td></td><td></td></tr>
</table>

Nichols Diagram	Root Locus	Comments
		Elementary instrument servo; inherently stable; gain margin = ∞
		Instrument servo with field control motor or power servo with elementary Wark-Leonard drive; stable as shown, but may become unstable with increased gain
		Elementary instrument servo with phase-lead (derivative) compensator; stable
		Inherently marginally stable; must be compensated

Transfer Function Plots for Typical Transfer Functions (continued)

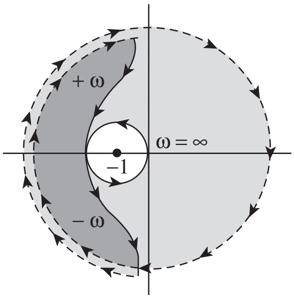
G(s)	Polar Plot	Bode Diagram
9. $\frac{K}{s^2(s\tau_1+1)}$		
10. $\frac{K(s\tau_a+1)}{s^2(s\tau_1+1)}$, $\tau_a > \tau_1$		
11. $\frac{K}{s^3}$		
12. $\frac{K(s\tau_a+1)}{s^3}$		

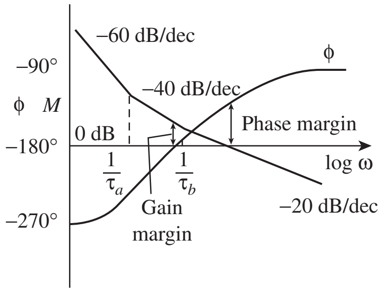
Nichols Diagram	Root Locus	Comments
		Inherently unstable; must be compensated
		Stable for all gains
		Inherently unstable
		Inherently unstable

Transfer Function Plots for Typical Transfer Functions (continued)

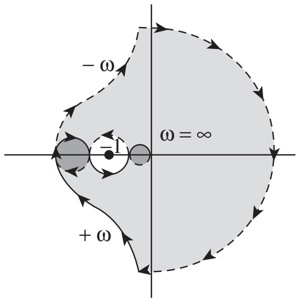
G(s) — Polar Plot — Bode Diagram

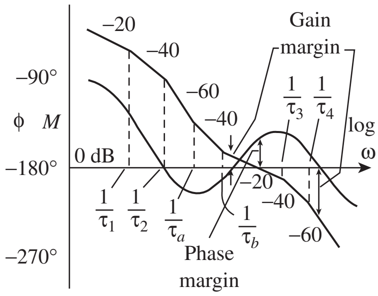
13. $\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s^3}$



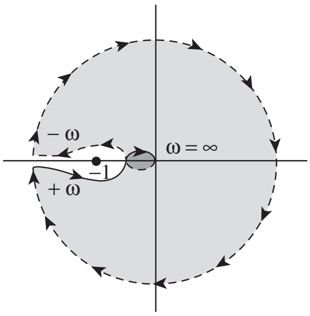


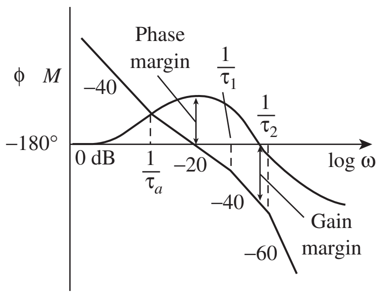
14. $\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s(s\tau_1+1)(s\tau_2+1)(s\tau_3+1)(s\tau_4+1)}$

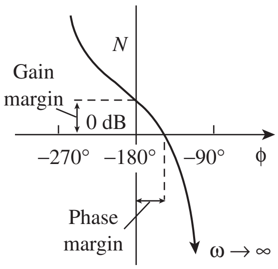
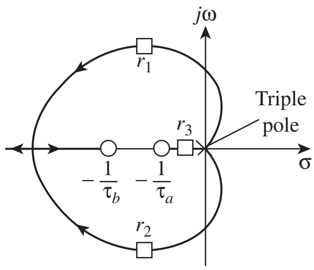
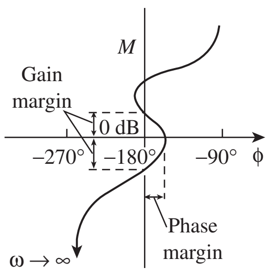
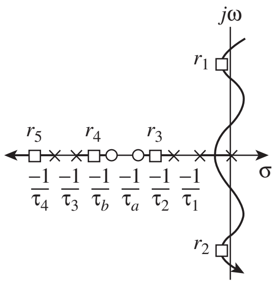
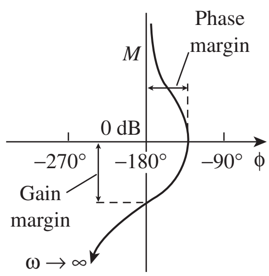
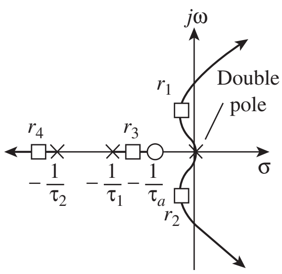




15. $\dfrac{K(s\tau_a+1)}{s^2(s\tau_1+1)(s\tau_2+1)}$





Nichols Diagram	Root Locus	Comments
		Conditionally stable; becomes unstable if gain is too low
		Conditionally stable; stable at low gain, becomes unstable as gain is raised, again becomes stable as gain is further increased, and becomes unstable for very high gains
		Conditionally stable; becomes unstable at high gain

From Dorf, R.C. and Bishop, R.H., Stability in the frequency domain, in *Modern Control Systems*, 9th ed., Prentice-Hall, Englewood Cliffs, NJ.

Fraction of Area Occupied by the Eight Primaries of the Neugebauer Model

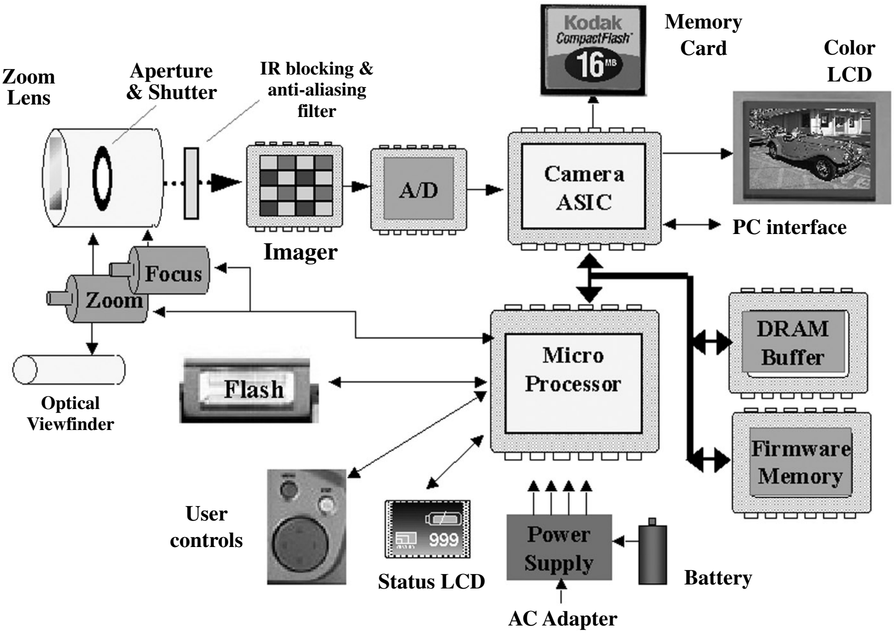
Primary	Ink Combination	Reflectance	Fraction of Area
White	—	$R_1(\lambda)$	$a_1 = (1-c)(1-m)(1-y)$
Cyan	Cyan	$R_2(\lambda)$	$a_2 = c(1-m)(1-y)$
Magenta	Magenta	$R_3(\lambda)$	$a_3 = (1-c)m(1-y)$
Yellow	Yellow	$R_4(\lambda)$	$a_4 = (1-c)(1-m)y$
Red	Magenta, yellow	$R_5(\lambda)$	$a_5 = (1-c)my$
Green	Cyan, yellow	$R_6(\lambda)$	$a_6 = c(1-m)y$
Blue	Cyan, magenta	$R_7(\lambda)$	$a_7 = cm(1-y)$
Black	Cyan, magenta, yellow	$R_8(\lambda)$	$a_8 = cmy$

From Emmel, P., Physical models for color prediction, in *Digital Color Imaging Handbook,* Sharma, G., Ed., CRC Press, Boca Raton, FL, 2003, p. 222.

Characterization vs. Calibration

	Characterization	Calibration
Stability	Stable with time (assumption)	Short-term drifts and environmental sensitivity
Process	Time consuming	Real-time, repeatable
Sensors	Expensive colorimetry	Inexpensive densitometry
Complexity	Three-dimensional or four-dimensional problem [3×3 matrix, 3-D lookup table (LUT) with interpolation, includes black]	One-dimensional problem (four LUTs)
Required by	Colorant characteristics, halftone orientation strategy	Dot gain, electrical and mechanical drift, d_{max}
Detail	Smooth functions	Detailed functions (can contain kinks and flat spots)
Method	Statistical averaging process	Measurement process

From Hains, C., Wang, S.-G., and Knox, K., Digital color halftones, in *Digital Color Imaging Handbook,* Sharma, G., Ed., CRC Press, Boca Raton, FL, 2003, p. 431.



Block diagram of the hardware components used in a typical digital camera. (From Parulski, K. and Spaulding, K., Color image processing for digital cameras, in *Digital Color Imaging Handbook,* Sharma, G., Ed., CRC Press, Boca Raton, FL, 2003, p. 729.)

Some Basic DTFT Pairs

	Sequence	Fourier Transform
1.	$\delta[n]$	1
2.	$\delta[n-n_0]$	$e^{-j\omega n_0}$
3.	$1\ (-\infty < n < \infty)$	$\sum_{k=-\infty}^{\infty} 2\pi\delta(\omega + 2k)$
4.	$a^n u[n]\ (\lvert a\rvert < 1)$	$\frac{1}{1-ae^{-j\omega}}$
5.	$u[n]$	$\frac{1}{1-e^{-j\omega}} + \sum_{k=-\infty}^{\infty} \pi\delta(\omega + 2\pi k)$
6.	$(n+1)a^n u[n]\ (\lvert a\rvert < 1)$	$\frac{1}{\left(1-ae^{-j\omega}\right)^2}$
7.	$\frac{r^2 \sin\omega_p (n+1)}{\sin\omega_p} u[n]\ (\lvert r\rvert < 1)$	$\frac{1}{1-2r\cos\omega_p e^{-j\omega} + r^2 e^{j2\omega}}$
8.	$\frac{\sin\omega_c n}{\pi n}$	$Xe^{j\omega} = \begin{cases} 1, & \lvert\omega\rvert < \omega_c \\ 0, & \omega_c < \lvert\omega\rvert \le \pi \end{cases}$

Some Basic DTFT Pairs (continued)

	Sequence	Fourier Transform
9.	$x[n] - \begin{cases} 1, & 0 \le n \le M \\ 0, & \text{otherwise} \end{cases}$	$\frac{\sin[\omega(M+1)/2]}{\sin(\omega/2)} = e^{-j\omega M/2}$
10.	$e^{j\omega n_0}$	$\sum_{k=-\infty}^{\infty} 2\pi\delta(\omega - \omega_0 + 2\pi k)$
11.	$\cos(\omega_0 n + \phi)$	$\pi \sum_{k=-\infty}^{\infty} [e^{j\phi}\delta(\omega - \omega_0 + 2\pi k) + e^{-j\phi}\delta(\omega + \omega_0 + 2\pi k)]$

From Jenkins, W.K., Fourier series, Fourier transforms, and the DFT, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **1**-12. Originally from A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, © 1989. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.

Properties of the DTFT

	Sequence	Fourier Transform
	$x[n]$	$X(e^{j\omega})$
	$y[n]$	$Y(e^{j\omega})$
1.	$ax[n] + by[n]$	$aX(e^{j\omega}) + bY(e^{j\omega})$
2.	$x[n - n_d]$ (n_d an integer)	$e^{-j\omega n} d\, X(e^{j\omega})$
3.	$e^{j\omega_0 n} x[n]$	$X(e^{j(\omega - \omega_0)})$
4.	$x[-n]$	$X(e^{-j\omega})$ if $x[n]$ is real $X^*(e^{j\omega})$
5.	$nx[n]$	$j\frac{dX(e^{j\omega})}{d\omega}$
6.	$x[n] * y[n]$	$X(e^{j\omega})\, Y(e^{j\omega})$
7.	$x[n]\, y[n]$	$\frac{1}{2\pi}\int_{-x}^{x} X(e^{j\theta})Y(e^{j(\omega-\theta)})d\theta$
	Parseval's Theorem	
8.	$\sum_{n=-\infty}^{\infty} \lvert x[n] \rvert^2 = \frac{1}{2\pi}\int_{-\pi}^{\pi} \lvert X(e^{j\omega}) \rvert^2 d\omega$	
9.	$\sum_{n=-\infty}^{\infty} x[n]y^*[n] = \frac{1}{2\pi} \inf_{-\pi}^{\pi} X(e^{j\omega})Y^*(e^{j\omega})d\omega$	

From Jenkins, W.K., Fourier series, Fourier transforms, and the DFT, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **1**-13. Originally from A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, © 1989. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.

Properties of the DFT

Finite-Length Sequence (Length N)		N-Point DFT (Length N)
1.	$x[n]$	$X[k]$
2.	$x_1[n], x_2[n]$	$X_1[k], X_2[k]$
3.	$ax_1[n] + bx_2[n]$	$aX_1[k] + bX_2[k]$
4.	$X[n]$	$Nx[((-k))_N]$
5.	$x[((n_m))_N]$	$W_N^{km}X[k]$
6.	$W_N^{-\ln}x[n]$	$X[((k-l))_N]$
7.	$\sum_{m=0}^{N-1} x_1(m)x_2[((n_m))_N]$	$X_1[k]X_2[k]$
8.	$x_1[n]x_2[n]$	$\frac{1}{N}\sum_{l=0}^{N-1} X_1(l)X_2[((k-l))_N]$
9.	$x^*[n]$	$X^*[((-k))_N]$
10.	$x^*[((-n))_N]$	$X^*[k]$
11.	$\text{Re}\{x[n]\}$	$x_{ep}[k] = \frac{1}{2}\{X[((k))_N] + K^*[((-k))_N]\}$
12.	$j\text{Im}\{x[n]\}$	$x_{op}[k] = \frac{1}{2}\{X[((k))_N] - X^*[((-k))_N]\}$
13.	$x_{ep}[n] = \frac{1}{2}\{x[n] + x^*[((-n))_N]\}$	$\text{Re}\{X[k]\}$
14.	$x_{op}[n] = \frac{1}{2}\{x[n] - x^*[((-n))_N]\}$	$j\text{Im}\{X[k]\}$
Properties 15–17 apply only when $x[n]$ is real		
15.	Symmetry properties	$\begin{cases} X[k] = X^*[((-k))_N] \\ \text{Re}\{X[k]\} = \text{Re}\{X[((-k))_N]\} \\ \text{Im}\{X[k]\} = -\text{Im}\{X[((-k))_N]\} \\ \lvert X[k]\rvert = \lvert X[((-k))_N]\rvert \\ \sphericalangle\{X[k]\} = -\sphericalangle\{X[((-k))_N]\} \end{cases}$
16.	$x_{ep}[n] = \frac{1}{2}\{x[n] + x[((-n))_N]\}$	$\text{Re}\{X[k]\}$
17.	$x_{op}[n] = \frac{1}{2}\{x[n] - x[((-n))_N]\}$	$j\text{Im}\{X[k]\}$

From Jenkins, W.K., Fourier series, Fourier transforms, and the DFT, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **1**-16. Originally from A.V. Oppenheim and R.W. Schafer, *Discrete-Time Signal Processing*, © 1989. Reprinted by permission of Prentice-Hall, Inc., Upper Saddle River, NJ.

Summary of the Four Types of Linear-Phase FIR Filters

	Odd Length (N)	Even Length (N)
Even symmetry	Type I	Type II
$h(\alpha + n) = h(\alpha - n)$	$\sum_{k=0}^{\frac{1}{2}[N-1]} a(k)\cos(\omega k)$	$\sum_{k=1}^{\frac{1}{2}N} b(k)\cos\left(\omega\left[k-\frac{1}{2}\right]\right)$
$\alpha = \frac{N-1}{2}$	$a(0) = h\left(\frac{N-1}{2}\right)$	zero at $\omega = \pi$
$\beta = 0$	$a(k) = 2h\left(\frac{N-1}{2} - k\right)$	$b(k) = 2h\left(\frac{N}{2} - k\right)$
		$\cos\left(\frac{1}{2}\omega\right)\sum_{k=0}^{\frac{1}{2}N-1} \hat{b}(k)\cos(\omega k)$
Odd symmetry	Type III	Type IV
$h(\alpha + n) = -h(\alpha - n)$	$\sum_{k=1}^{\frac{1}{2}[N-1]} c(k)\sin(\omega k)$	$\sum_{k=1}^{\frac{1}{2}N} d(k)\sin\left(\omega\left[k-\frac{1}{2}\right]\right)$
$\alpha = \frac{N-1}{2}$	zeros at $\omega = 0, \pi$	zero at $\omega = 0$
$\beta = \frac{\pi}{2}$	$c(k) = 2h\left(\frac{N-1}{2} - k\right)$	$d(k) = 2h\left(\frac{N}{2} - k\right)$
	$h\left(\frac{N-1}{2}\right) = 0$	
	$\sin(\omega)\sum_{k=0}^{\alpha-1} \hat{c}(k)\cos(\omega k)$	$\sin\left(\frac{1}{2}\omega\right)\sum_{k=0}^{\frac{1}{2}N-1} \hat{d}(k)\cos(\omega k)$

From Karam, L.J., McClellan, J.H., and Selesnick, I.W., Digital filtering, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **11**-12.

Basic Parameters for Three Classes of Acoustic Signals

	Frequency Range in Hz	Sampling Rate in kHz	PCM Bis per Sample	PCM Bit Rate in kb/s
Telephone speech	300–3,400[a]	8	8	64
Wideband speech	50–7,000	16	8	128
Wideband audio (stereo)	10–20,000	48[b]	2 × 16	2 × 768

[a] Bandwidth in Europe; 200 to 3200 Hz in the U.S.
[b] Other sampling rates: 44.1 kHz, 32 kHz.

From Noll, P., MPEG digital audio coding standards, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **40**-2.

CD and DAT Bit Rates

Storage Device	Audio Rate (Mb/s)	Overhead (Mb/s)	Total Bit Rate (Mb/s)
Compact disc (CD)	1.41	2.91	4.32
Digital audio tape (DAT)	1.41	1.05	2.46

Note: Stereophonic signals, sampled at 44.1 kHz; DAT supports also sampling rates of 32 kHz and 48 kHz.

From Noll, P., MPEG digital audio coding standards, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **40**-2.

Summary of the Functionalities and Characteristics of the Existing Standards

	ITU		ISO		
Attribute	H.261	H.263	MPEG-1	MPEG-2	MPEG-4
Applications	Video-conferencing	Video-phone	CD storage	Broadcast	Wide range (multimedia)
Bit rate	64K–1M	<64 K	1.0–1.5M	2–10M	5K–4M
Material	Progressive	Progressive	Progressive, interlaced	Progressive, interlaced	Progressive, interlaced
Object shape	Rectangular	Arbitrary (simple)	Rectangular	Rectangular	Arbitrary
			Residual Coding		
Transform	8 × 8 DCT	8 × 8 DCT	8 × 8 DCT	8 × 8 DCT	8 × 8 DCT
Quantizer	Uniform	Uniform	Weighted uniform	Weighted uniform	Weighted uniform
			Motion Compensation		
Type	Block	Block	Block	Block	Block, sprites
Block size	16 × 16	16 × 16, 8 × 8	16 × 16	16 × 16	16 × 16, 8 × 8
Prediction type	Forward	Forward, backward	Forward backward	Forward, backward	Forward, backward
Accuracy	One pixel	Half pixel	Half pixel	Half pixel	Half pixel
Loop filter	Yes	No	No	No	No
			Scalability		
Temporal	No	Yes	Yes	Yes	Yes
Spatial	No	Yes	No	Yes	Yes
Bit rate	No	Yes	No	Yes	Yes
Object	No	No	No	No	Yes

From Al-Shaykh, O., Neff, R., Taubman, D., and Zakhor, A., Video sequence compression, in *The Digital Signal Processing Handbook*, Madisetti, V.K. and Williams, D.B., Eds., CRC Press, Boca Raton, FL, 1998, p. **55**-16.

EV and ICEV Efficiencies from Crude Oil to Traction Effort

ICEV	Efficiency (%) Max.	Efficiency (%) Min.	EV	Efficiency (%) Max.	Efficiency (%) Min.
Crude oil			Crude oil		
Refinery (petroleum)	90	85	Refinery (fuel oil)	97	95
Distribution to fuel tank	99	95	Electricity generation	40	33
Engine	22	20	Transmission to wall outlet	92	90
Transmission/axle	98	95	Battery charger	90	85
Wheels			Battery (lead/acid)	75	75
			Motor/controller	85	80
			Transmission/axle	98	95
			Wheels		
Overall efficiency (crude oil to wheels)	19	15	Overall efficiency (crude oil to wheels)	20	14

From Husain, I., Inroduction to electric vehicles, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 12.

Nominal Energy Density of Sources

Energy Source	Nominal Specific Energy (Wh/kg)
Gasoline	12,500
Natural gas	9350
Methanol	6050
Hydrogen	33,000
Coal (bituminous)	8200
Lead-acid battery	35
Lithium-polymer battery	200
Flywheel (carbon-fiber)	200

From Husain, I., Energy Source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 44.

Specific Energy of Batteries

Battery	Specific Energy (Wh/kg) Theoretical	Specific Energy (Wh/kg) Practical
Lead-acid	108	50
Nickel-cadmium		20–30
Nickel-zinc		90
Nickel-iron		60
Zinc-chlorine		90
Silver-zinc	500	100
Sodium-sulfur	770	150–300
Aluminum-air		300

From Husain, I., Energy source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 47.

USABC Objectives for EV Battery Packs

Parameter	Mid-Term	Commercialization	Long-Term
Specific energy (Wh/kg) (C/3 discharge rate)	80–100	150	200
Energy density (Wh/liter) (C/3 discharge rate)	135	230	300
Specific power (W/kg)(80% *DoD* per 30 s)	150–200	300	400
Specific power (W/kg), Regen. (20% *DoD* per 10 s)	75	150	200
Power density (W/liter)	250	460	600
Recharge time, h (20% → 100% *SoC*)	<6	4–6	3–6
Fast recharge time, min	<15	<30	<15
Calendar life, years	5	10	10
Life, cycles	600 @ 80% *DoD*	1000 @ 80% *DoD* 1600 @ 50% *DoD* 2670 @ 30% *DoD*	1000 @ 80% *DoD*
Lifetime urban range, miles	100,000	100,000	100,000
Operating environment, °C	–30 to +65	–40 to +50	–40 to +85
Cost, US$/kWh	<150	<150	<100
Efficiency, %	75	80	80

From Husain, I., Energy Source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 68.

Properties of EV and HEV Batteries

Battery Type	Specific Energy, Wh/kg	Specific Power, W/kg	Energy Efficiency, %	Cycle Life	Estimated Cost, US$/*kWh*
Lead-acid	35–50	150–400	80	500–1000	100–150
Nickel-cadmium	30–50	100–150	75	1000–2000	250–350
Nickel-metal-hydride	60–80	200–300	70	1000–2000	200–350
Aluminum-air	200–300	100	<50	Not available	Not available
Zinc-air	100–220	30–80	60	500	90–120
Sodium-sulfur	150–240	230	85	1000	200–350
Sodium-nickel-chloride	90–120	130–160	80	1000	250–350
Lithium-polymer	150–200	350	Not available	1000	150
Lithium-ion	80–130	200–300	>95	1000	200

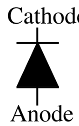
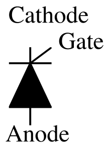
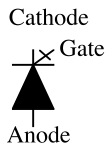
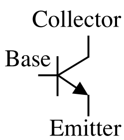
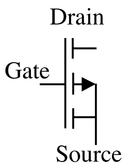
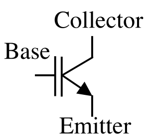
From Husain, I., Energy Source: Battery, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 68.

Fuel Cell Types

Fuel Cell Variety	Fuel	Electrolyte	Operating Temperature	Efficiency	Applications
Phosphoric acid	H_2, reformate (LNG, methanol)	Phosphoric acid	~200°C	40–50%	Stationary (>250 kW)
Alkaline	H_2	Potassium hydroxide solution	~80°C	40–50%	Mobile
Proton exchange membrane	H_2, reformate (LNG, methanol)	Polymer ion exchange film	~80°C	40–50%	EV and HEV, industrial up to ~80 kW
Direct methanol	Methanol, ethanol	Solid polymer	90–100°C	~30%	EV and HEVs, small portable devices (1 W to 70 kW)
Molten carbonate	H_2, CO (coal gas, LNG, methanol)	Carbonate	600–700°C	50–60%	Stationary (>250 kW)
Solid oxide	H_2, CO (coal gas, LNG, methanol)	Yttria-stabilized zirconia	~1000°C	50–65%	Stationary

From Husain, I., Alternative energy sources, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 86.

Summary of Power Devices

Name	Symbol	Turn On	Turn Off	Comments
Diode		• Positive anode to cathode voltage	• Reverse anode current • Recovery time before turning off	• Turn off and on depend on circuit conditions • High power capabilities
SCR		• Small gate pulse (current) • Slow to medium turn-on time (~5 µs)	• Anode current goes below holding • Delay time before forward voltage can be applied (10–200 µs)	• Very high power • Needs additional circuit to turn off • On voltage ≈2.5 V
GTO		• Small gate pulse (current) • Slow to medium turn-on time (~10 µs)	• Remove charge from gate (medium current) • Medium speed (~0.5 µs)	• High power • Easier to turn off than SCR • On voltage ≈2.5 V
BJT		• Medium current to base to turn on • Medium speed (0.5 µs)	• Remove current from base • Medium speed (0.2 µs)	• Medium power • Easy to control • Medium drive requirements • On voltage ≈1.5 V
MOSFET		• Voltage to gate (v_{GS}) • Very high speed (0.2 µs)	• Remove voltage from gate • High speed (0.5 µs)	• Low power • Very easy to control • Simple gate drive requirement • High on losses ≈0.1 Ω on resistance
IGBT		• Voltage to gate (v_{GS}) • High speed (0.4 µs)	• Remove voltage from gate • High speed (~0.7 µs)	• Medium power • Very easy to control • On voltage ≈3.0 V • Combines MOS and BJT technologies

From Husain, I., Power electronics and motor drives, in *Electric and Hybrid Vehicles: Design Fundamentals,* CRC Press, Boca Raton, FL, 2003, p. 165.

Wind Power Installed Capacity	
Canada	83
China	224
Denmark	1450
India	968
Ireland	63
Italy	180
Germany	2874
Netherlands	363
Portugal	60
Spain	834
Sweden	150
U.K.	334
U.S.	1952
Other	304
Total	9839

From Johnson, G.L., Wind power, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **1**-2.

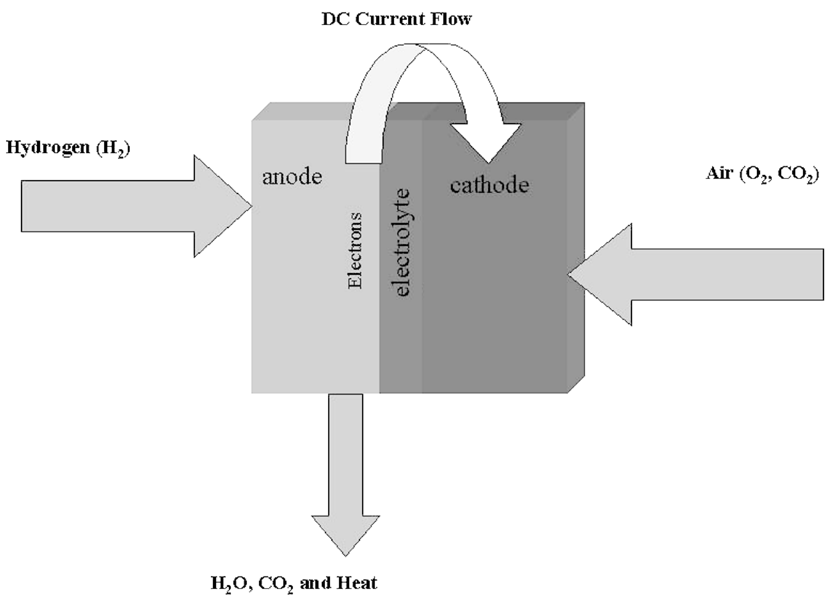
Comparison of Five Fuel Cell Technologies

Type	Electrolyte	Operating Temperature (°C)	Applications	Advantages
Polymer Electrolyte Membrane (PEM)	Solid organic polymer poly-perflouro-sulfonic acid	60–100	Electric utility, transportation, portable power	Solid electrolyte reduces corrosion, low temperature, quick start-up
Alkaline (AFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90–100	Military, space	Cathode reaction faster in alkaline electrolyte; therefore high performance
Phosphoric Acid (PAFC)	Liquid phosphoric acid soaked in a matrix	175–200	Electric utility, transportation, and heat	Up to 85% efficiency in co-generation of electricity
Molten Carbonate (MCFC)	Liquid solution of lithium, sodium, and/or potassium carbonates soaked in a matrix	600–1000	Electric utility	Higher efficiency, fuel flexibility, inexpensive catalysts
Solid Oxide (SOFC)	Solid zirconium oxide to which a small amount of yttria is added	600–1000	Electric utility	Higher efficiency, fuel flexibility, inexpensive catalysts. Solid electrolyte advantages like PEM

From Rahman, S., Advanced energy technologies, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **1**-12.

Technology	Size	Fuel Sources	AC interface Type	Applications
Fuel Cells	.5Kw – Larger units With Stacking	Natural Gas Hydrogen Petroleum Products	Inverter type	Continuous
Microturbines	10Kw–100Kw Larger sizes	Natural Gas Petroleum Products	Inverter type	Continuous Standby
Batteries	.1Kw–2Mw+	Storage	Inverter type	PQ, Peaking
Flywheel	>.1Kw–.5Kw	Storage	Inverter type	PQ, Peaking
PV	>.1Kw–1Kw	Sunlight	Inverter type	Peaking
Gas Turbine	10Kw–5Mw+	Natural Gas Petroleum Products	Rotary type	Continuous, Peaking Standby

Distributed generation technology chart. (From Kennedy, J.R., Distributed utilities, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-28.)



Basic fuel cell operation. (From Kennedy, J.R., Distributed utilities, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-29.)

Usual Operating Conditions for Transformers (ANSI/IEEE, C57.12.01-1989 (R1998))

Temperature of cooling air	≤40°C
24hr average temperature of cooling air	≤30°C
Minimum ambient temperature	≥–30°C
Load current[a]	Harmonic factor ≤0.05 per unit
Altitude[b]	≤3300 ft (1000 m)
Voltage[c] (without exceeding limiting temperature rise)	• Rated output KVA at 105% rated secondary voltage, power factor ≥0.80 • 110% rated secondary voltage at no load

[a] Any unusual load duty should be specified to the manufacturer.
[b] At higher altitudes, the reduced air density decreases dielectric strength; it also increases temperature rise reducing capability to dissipate heat losses (ANSI/IEEE, C57.12.01-1989 (R1998)).
[c] Operating voltage in excess of rating may cause core saturation and excessive stray losses, which could result in overheating and excessive noise levels (ANSI/IEEE, C57.94-1982 (R1987), C57.12.01-1989 (R1998)).

From Payne, P.A., Dry type transformers, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **3**-65.

Resistivity and Temperature Coefficient of Some Materials

Material	Resistivity at 20°C (Ω-m)	Temperature Coefficient (°C)
Silver	1.59×10^{-8}	243.0
Annealed copper	1.72×10^{-8}	234.5
Hard-drawn copper	1.77×10^{-8}	241.5
Aluminum	2.83×10^{-8}	228.1

From Reta-Hernandez, M., Transmission line parameters, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **4**-65.

Most Commonly Found Relays for Generator Protection

Identification Number	Function Description	Relay Type
87G	Generator phase phase windings protection	Differential protection
87T	Step-up transformer differential protection	Differential protection
87U	Combined differential transformer and generator protection	Differential protection
40	Protection against the loss of field voltage or current supply	Offset mho relay
46	Protection against current imbalance. Measurement of phase negative sequence current	Time-overcurrent relay
32	Anti-motoring protection	Reverse-power relay
24	Overexcitation protection	Volt/Hertz relay
59	Phase overvoltage protection	Overvoltage relay
60	Detection of blown voltage transformer fuses	Voltage balance relay
81	Under- and overfrequency protection	Frequency relays
51V	Backup protection against system faults	Voltage controlled or voltage-restrained time overcurrent relay
21	Backup protection against system faults	Distance relay
78	Protection against loss of synchronization	Combination of offset mho and blinders

From Benmouyal, G., The protection of synchronous generators, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-12.

Appliances and Sectors under Direct Utility Control, U.S. — 1983

Appliance or Sector	Number Controlled	Percent of Total Controlled
Electric water heaters	648,437	43%
Air conditioners	515,252	34%
Irrigation pumps	14,261	1%
Space heating	50,238	3%
Swimming pool pumps	258,993	17%
Other	13,710	1%
Total	**1,500,891**	**100%**
Residential	1,456,212	97%
Commercial	29,830	2%
Industrial	588	—
Agricultural	14,261	1%

From Merrill, H.M., Power system planning, in *The Electric Power Engineering Handbook,* Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001, p. **13**-43. Originally from *New Electric Power Technologies: Problems and Prospects for the 1990s,* Washington, D.C.: U.S. Congress, Office of Technology Assessment, OTA-E-246, July 1985.

Typical Characteristics of Integrated Circuit Resistors

Resistor Type	Sheet Resistivity (per square)	Temperature Coefficient (ppm/°C)
Semiconductor		
Diffused	0.8 to 260 Ω	1100 to 2000
Bulk	0.003 to 10 kΩ	2900 to 5000
Pinched	0.001 to 10 kΩ	3000 to 6000
Ion-implanted	0.5 to 20 kΩ	100 to 1300
Deposited resistors		
Thin-film		
Tantalum	0.01 to 1 kΩ	∓100
SnO_2	0.08 to 4 kΩ	–1500 to 0
Ni-Cr	40 to 450 Ω	∓100
Cermet (Cr-SiO)	0.03 to 2.5 kΩ	∓150
Thick-film		
Ruthenium-silver	10 Ω to 10 MΩ	∓200
Palladium-silver	0.01 to 100 kΩ	–500 to 150

From Pecht, M. and Lall, P., Resistors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 13.

Speech Coder Performance Comparisons

Algorithm (acronym)	Standardization		Rate kbits/s	Subjective		
	Body	Identifier		MOS	DRT	DAM
μ-law PCM	ITU-T	G.711	64	4.3	95	73
ADPCM	ITU-T	G.721	32	4.1	94	68
LD-CELP	ITU-T	G.728	16	4.0	94[a]	70[a]
RPE-LTP	GSM	GSM	13	3.5	—	—
VSELP	CTIA	IS-54	8	3.5	—	—
CELP	U.S. DoD	FS-1016	4.8	3.13[b]	90.7[b]	65.4[b]
IMBE	Inmarsat	IMBE	4.1	3.4	—	—
LPC-10e	U.S. DoD	FS-1015	2.4	2.24[b]	86.2[b]	50.3[b]

[a] Estimated.
[b] From results of 1996 U.S. DoD 2400 bits/s vocoder competition.

From McClellan, S. and Gibson, J.D., Coding, transmission, and storage, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 345.

Surface Mount Substrate Material

Substrate Material (Units)	T_g – Glass Transition Temperature (°C)	TCE – Thermal Coefficient of X–Y Expansion (PPM/°C)	Thermal Conductivity (W/M°C)	Moisture Absorption (%)
FR-4 Epoxy glass	125	13–18	0.16	0.10
Polymide glass	250	12–16	0.35	0.35
Copper-clad invar	Depends on resin	5–7	160XY — 15–20Z	NA
Poly Aramid fiber	250	3–8	0.15	1.65
Alumina/ceramic	NA	5–7	20–45	NA

From Blackwell, G.R., Surfact mount technology, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 692.

Emissivities of Some Common Materials

Material	Temperature (°C)	Emissivity
Tungsten	2000	0.28
Nickel-chromium (80-20)	600	0.87
Lampblack	20–400	0.96
Polished silver	200	0.02
Glass	1000	0.72
Platinum	600	0.1
Graphite	3600	0.8
Aluminum (oxidized)	600	0.16
Carbon filament	1400	0.53

From Watkins, L.S., Sources and detectors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 818.

Thermal Conductivities of Typical Packaging Materials at Room Temperature

Materials	Thermal Conductivity (W/m K)
Air	0.024
Mylar	0.19
Silicone rubber	0.19
Solder mask	0.21
Epoxy (dielectric)	0.23
Ablefilm 550 dielectric	0.24
Nylon	0.24
Polytetrafluorethylene	0.24
RTV	0.31
Polyimide	0.33
Epoxy (conductive)	0.35
Water	0.59
Mica	0.71
Ablefilm 550 K	0.78
Thermal greases/pastes	1.10
Borosilicate glass	1.67
Glass epoxy	1.70
Stainless steel	15
Kovar	16.60
Solder (Pb-In)	22
Alumina	25
Solder 80-20 Au-Sn	52
Silicon	118
Molybdenum	138
Aluminum	156
Beryllia	242
Gold	298
Copper	395
Silver	419
Diamond	2000

From Bar-Cohen, A., Thermal management of electronics, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 855. Originally from C.A. Harper, *Electronic Packaging and Interconnection Handbook,* New York: McGraw-Hill, 1991, p. 27. R.R. Tummala and E.J. Rymaszewski, *Microelectronics Packaging Handbook,* New York: Van Nostrand Reinhold, 1989, p. 174.

Relative Permeability, μ_r, of Some Diamagnetic, Paramagnetic, and Ferromagnetic Materials

Material	μr	M_s, A/m²
Diamagnetics		
Bismuth	0.999833	
Mercury	0.999968	
Silver	0.9999736	
Lead	0.9999831	
Copper	0.9999906	
Water	0.9999912	
Paraffin wax	0.99999942	
Paramagnetics		
Oxygen (s.t.p.)	1.000002	
Air	1.00000037	
Aluminum	1.000021	
Tungsten	1.00008	
Platinum	1.0003	
Manganese	1.001	
Ferromagnetics		
Purified iron: 99.96% Fe	280,000	2.158
Motor-grade iron: 99.6% Fe	5,000	2.12
Permalloy: 78.5% Ni, 21.5% Fe	70,000	2.00
Supermalloy: 79% Ni, 15% Fe, 5% Mo, 0.5% Mn	1,000,000	0.79
Permendur: 49% Fe, 49% Ca, 2% V	5,000	2.36
Ferrimagnetics		
Manganese–zinc ferrite	750	0.34
	1,200	0.36
Nickel–zinc ferrite	650	0.29

From Bate, G., Magnetism, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 902. Originally from F. Brailsford, *Physical Principles of Magnetism*, London: Van Nostrand, 1966. With permission.

"Hard" and "Soft" Magnetic Materials

	High M_s	Low H_c	Low M_r	High μ
Soft				
Fe	1700 emu/cc	1 Oe	<500	20,000
80 Ni 20 Fe	660	0.1	<300	50,000
Mn Zn ferrite	400	0.02	<200	5,000
$Co_{70}Fe_5Si_{15}B_{10}$	530	0.1	<250	10,000
	High M_s	High H_c	High M_r	T_c
Hard				
Particles				
γ-Fe_2O_3	400	250–450	200–300	115–126
CrO_2	400	450–600	300	120
Fe	870–1100	1100–1500	435–550	768
$BaO.6Fe_2O_3$	238–370	800–3000	143–260	320
Alloys				
$SmCo_5$	875	40,000	690	720
Sm_2Co_{17}	1000	17,000	875	920
$Fe_{14}BNd_2$	1020	12,000	980	310

From Bate, G., Magnetism, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 908.

Standard Rectangular Waveguides

EIA[a] Designation WR[b]( )	Physical Dimensions: Inside, cm (in.) Width	Inside, cm (in.) Height	Outside, cm (in.) Width	Outside, cm (in.) Height	Cut-off Frequency for Air-filled Waveguide, GHz	Recommended Frequency Range for TE_{10} Mode, GHZ
2300	58.420 (23.000)	29.210 (11.500)	59.055 (23.250)	29.845 (11.750)	0.257	0.32–0.49
2100	53.340 (21.000)	26.670 (10.500)	53.973 (21.250)	27.305 (10.750)	0.281	0.35–0.53
1800	45.720 (18.000)	22.860 (9.000)	46.350 (18.250)	23.495 (9.250)	0.328	0.41–0.62
1500	38.100 (15.000)	19.050 (7.500)	38.735 (15.250)	19.685 (7.750)	0.394	0.49–0.75
1150	29.210 (11.500)	14.605 (5.750)	29.845 (11.750)	15.240 (6.000)	0.514	0.64–0.98
975	24.765 (9.750)	12.383 (4.875)	25.400 (10.000)	13.018 (5.125)	0.606	0.76–1.15
770	19.550 (7.700)	9.779 (3.850)	20.244 (7.970)	10.414 (4.100)	0.767	0.96–1.46
650	16.510 (6.500)	8.255 (3.250)	16.916 (6.660)	8.661 (3.410)	0.909	1.14–1.73
510	12.954 (5.100)	6.477 (2.500)	13.360 (5.260)	6.883 (2.710)	1.158	1.45–2.20
430	10.922 (4.300)	5.461 (2.150)	11.328 (4.460)	5.867 (2.310)	1.373	1.72–2.61
340	8.636 (3.400)	4.318 (1.700)	9.042 (3.560)	4.724 (1.860)	1.737	2.17–3.30
284	7.214 (2.840)	3.404 (1.340)	7.620 (3.000)	3.810 (1.500)	2.079	2.60–3.95
229	5.817 (2.290)	2.908 (1.145)	6.142 (2.418)	3.233 (1.273)	2.579	3.22–4.90
187	4.755 (1.872)	2.215 (0.872)	5.080 (2.000)	2.540 (1.000)	3.155	3.94–5.99
159	4.039 (1.590)	2.019 (0.795)	4.364 (1.718)	2.344 (0.923)	3.714	4.64–7.05
137	3.485 (1.372)	1.580 (0.622)	3.810 (1.500)	1.905 (0.750)	4.304	5.38–8.17
112	2.850 (1.122)	1.262 (0.497)	3.175 (1.250)	1.588 (0.625)	5.263	6.57–9.99
90	2.286 (0.900)	1.016 (0.400)	2.540 (1.000)	1.270 (0.500)	6.562	8.20–12.50
75	1.905 (0.750)	0.953 (0.375)	2.159 (0.850)	1.207 (0.475)	7.874	9.84–15.00
62	1.580 (0.622)	0.790 (0.311)	1.783 (0.702)	0.993 (0.391)	9.494	11.90–18.00
51	1.295 (0.510)	0.648 (0.255)	1.499 (0.590)	0.851 (0.335)	11.583	14.50–22.00
42	1.067 (0.420)	0.432 (0.170)	1.270 (0.500)	0.635 (0.250)	14.058	17.60–26.70
34	0.864 (0.340)	0.432 (0.170)	1.067 (0.420)	0.635 (0.250)	17.361	21.70–33.00
28	0.711 (0.280)	0.356 (0.140)	0.914 (0.360)	0.559 (0.220)	21.097	26.40–40.00
22	0.569 (0.224)	0.284 (0.112)	0.772 (0.304)	0.488 (0.192)	26.362	32.90–50.10
19	0.478 (0.188)	0.239 (0.094)	0.681 (0.268)	0.442 (0.174)	31.381	39.20–59.60

Standard Rectangular Waveguides (continued)

EIA[a] Designation WR[b]( )	Physical Dimensions: Inside, cm (in.) Width	Height	Outside, cm (in.) Width	Height	Cut-off Frequency for Air-filled Waveguide, GHz	Recommended Frequency Range for TE_{10} Mode, GHZ
15	0.376 (0.148)	0.188 (0.074)	0.579 (0.228)	0.391 (0.154)	39.894	49.80–75.80
12	0.310 (0.122)	0.155 (0.061)	0.513 (0.202)	0.358 (0.141)	48.387	60.50–91.90
10	0.254 (0.100)	0.127 (0.050)	0.457 (0.180)	0.330 (0.130)	59.055	73.80–112.00
8	0.203 (0.080)	0.102 (0.040)	0.406 (0.160)	0.305 (0.120)	73.892	92.20–140.00
7	0.165 (0.065)	0.084 (0.033)	0.343 (0.135)	0.262 (0.103)	90.909	114.00–173.00
5	0.130 (0.051)	0.066 (0.026)	0.257 (0.101)	0.193 (0.076)	115.385	145.00–220.00
4	0.109 (0.043)	0.056 (0.022)	0.211 (0.083)	0.157 (0.062)	137.615	172.00–261.00
3	0.086 (0.034)	0.043 (0.017)	0.163 (0.064)	0.119 (0.047)	174.419	217.00–333.00

[a] Electronic Industry Association.
[b] Rectangular waveguide.

From Demarest, K., Waveguides, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 947. Originally from S.Y. Liao, *Microwave Devices and Circuits,* 3rd ed., Englewood Cliffs, NJ: Prentice-Hall, 1990, p. 118. With permission.

Material Parameters for Several Semiconductors

Semiconductor	E_g (eV)	ε_r	κ (W/cm-K) @300 K	E_c (V/cm)	$\tau_{minority}$ (s)
Si	1.12	11.9	1.5	3×10^5	2.5×10^{-3}
GaAs	1.42	12.5	0.54	4×10^5	$\sim 10^{-8}$
InP	1.34	12.4	0.67	4.5×10^5	$\sim 10^{-8}$
α-SiC	2.86	10.0	4	$(1–5) \times 10^6$	$\sim(1–10) \times 10^{-9}$
β-SiC	2.2	9.7	4	$(1–5) \times 10^6$	$\sim(1–10) \times 10^{-9}$

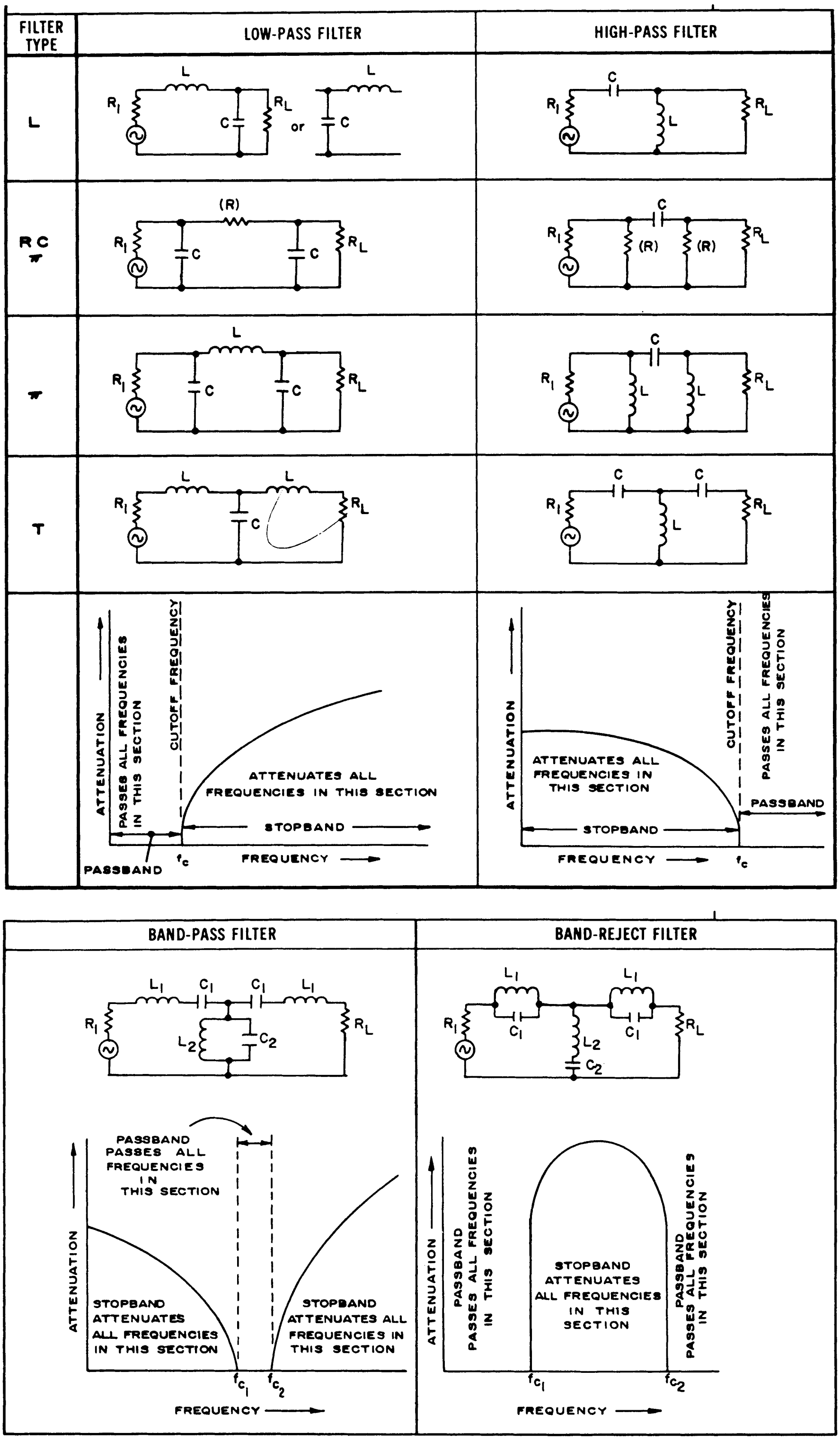
From Trew, R.J., Active microwave devices, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 991.

Absorption Loss Is a Function of Type of Material and Frequency (Loss Shown Is at 150 kHz)

Metal	Relative Conductivity	Relative Permeability	Absorption Loss *A*, dB/mm
Silver	1.05	1	52
Copper—annealed	1.00	1	51
Copper—hard drawn	0.97	1	50
Gold	0.70	1	42
Aluminum	0.61	1	40
Magnesium	0.38	1	31
Zinc	0.29	1	28
Brass	0.26	1	26
Cadmium	0.23	1	24
Nickel	0.20	1	23
Phosphor–bronze	0.18	1	22
Iron	0.17	1000	650
Tin	0.15	1	20
Steel, SAE1045	0.10	1000	500
Beryllium	0.10	1	16
Lead	0.08	1	14
Hypernik	0.06	80000	3500[a]
Monel	0.04	1	10
Mu-metal	0.03	80000	2500[a]
Permalloy	0.03	80000	2500[a]
Steel, stainless	0.02	1000	220[a]

[a] Assuming that material is not saturated.

From Hemmings, L.H., Grounding, shielding, and filtering, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1007.



Filters provide a variety of frequency characteristics. (From Hemmings, L.H., Grounding, shielding, and filtering, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1012.)

Radar Bands

Band	Frequency Range	Principal Applications
HF	3–30 MHz	Over-the-horizon radar
VHF	30–300 MHz	Long-range search
UHF	300–1000 MHz	Long-range surveillance
L	1000–2000 MHz	Long-range surveillance
S	2000–4000 MHz	Surveillance
		Long-range weather characterization
		Terminal air traffic control
C	4000–8000 MHz	Fire control
		Instrumentation tracking
X	8–12 GHz	Fire control
		Air-to-air missile seeker
		Marine radar
		Airborne weather characterization
Ku	12–18 GHz	Short-range fire control
		Remote sensing
Ka	27–40 GHz	Remote sensing
		Weapon guidance
V	40–75 GHz	Remote sensing
		Weapon guidance
W	75–110 GHz	Remote sensing
		Weapon guidance

From Belcher, Jr., M.L. and Nessmith, J.T., Pulse radar, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1044.

Typical Acoustic Properties

Material	Velocity (km/s) Longitudinal	Velocity (km/s) Shear	Impedance ($kg/m^2 s \times 10^6$) Longitudinal	Impedance ($kg/m^2 s \times 10^6$) Shear	Density ($kg/m^3 \times 10^3$)	Comments
Alcohol, methanol	1.103		0.872		0.791	Liq. 25°C
Aluminum, rolled	6.42	3.04	17.33	8.21	2.70	Isot.
Brass, 70% Cu, 30% Zn	4.70	2.10	40.6	18.14	8.64	Isot.
Cadmium sulphide	4.46	1.76	21.5	8.5	4.82	Piez crys *Z*-dir
Castor oil	1.507		1.42		0.942	Liq. 20°C
Chromium	6.65	4.03	46.6	28.21	7.0	Isot.
Copper, rolled	5.01	2.27	44.6	20.2	8.93	Isot.
Ethylene glycol	1.658		1.845		1.113	Liq. 25°C
Fused quartz	5.96	3.76	13.1	8.26	2.20	Isot.
Glass, crown	5.1	2.8	11.4	6.26	2.24	Isot.
Gold, hard drawn	3.24	1.20	63.8	23.6	19.7	Isot.
Iron, cast	5.9	3.2	46.4	24.6	7.69	Isot.
Lead	2.2	0.7	24.6	7.83	11.2	Isot.
Lithium niobate, $LiNbO_3$	6.57	4.08	30.9	19.17	4.70	Piez crys *X*-dir
		4.79		22.53		
Nickel	5.6	3.0	49.5	26.5	8.84	Isot.
Polystyrene, styron	2.40	1.15	2.52	1.21	1.05	Isot.
PZT-5H	4.60	1.75	34.5	13.1	7.50	Piez ceram *Z*
Quartz	5.74	3.3	15.2	8.7	2.65	Piez crys *X*-dir
		5.1		13.5		
Sapphire Al_2O_3	11.1	6.04	44.3	25.2	3.99	Cryst. *Z*-axis
Silver	3.6	1.6	38.0	16.9	10.6	Isot.
Steel, mild	5.9	3.2	46.0	24.9	7.80	Isot.
Tin	3.3	1.7	24.2	12.5	7.3	Isot.
Titanium	6.1	3.1	27.3	13.9	4.48	Isot.
Water	1.48		1.48		1.00	Liq. 20°C
YAG $Y_3Al_{15}O_{12}$	8.57	5.03	39.0	22.9	4.55	Cryst. *Z*-axis
Zinc	4.2	2.4	29.6	16.9	7.0	Isot.
Zinc oxide	6.37	2.73	36.1	15.47	5.67	Piez crys *Z*-dir

From Farnell, G.W., Ultrasound, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1171.

Ferroelectric, Piezoelectric, and Electrostrictive Materials

Type	Material Class	Example	Applications
Electret	Organic	Waxes	No recent
Electret	Organic	Fluorine based	Microphones
Ferroelectric	Organic	PVF2	No known
Ferroelectric	Organic	Liquid crystals	Displays
Ferroelectric	Ceramic	PZT thin film	NV-memory
Piezoelectric	Organic	PVF2	Transducer
Piezoelectric	Ceramic	PZT	Transducer
Piezoelectric	Ceramic	PLZT	Optical
Piezoelectric	Single crystal	Quartz	Freq. control
Piezoelectric	Single crystal	$LiNbO_3$	SAW devices
Electrostrictive	Ceramic	PMN	Actuators

From Etzold, K.F., Ferroelectric and piezoelectric materials, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1180.

Material Parameters for Type I Superconductors*

Material	T_c (K)	λ_o (nm)	ξ_o (nm)	Δ_o (meV)	$\mu_0 H_{co}$ (mT)
Al	1.18	50	1600	0.18	110.5
In	3.41	65	360	0.54	123.0
Sn	3.72	50	230	0.59	130.5
Pb	7.20	40	90	1.35	180.0
Nb	9.25	85	40	1.50	198.0

* The penetration depth λ_o is given at zero temperature, as are the coherence length ξ_o, the thermodynamic critical field H_{co}, and the energy gap Δ_o.

From Delin, K.A. and Orlando, T.P., Superconductivity, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1224. Originally from R.J. Donnelly, "Cryogenics," in *Physics Vade Mecum,* H.L. Anderson, Ed., New York: American Institute of Physics, 1981. With permission.

Material Parameters for Conventional Type II Superconductors*

Material	T_c (K)	$\lambda_{GL}(0)$ (nm)	$\xi_{GL}(0)$ (nm)	Δ_o (meV)	$\mu_0 H_{c2,o}$ (T)
Pb-In	7.0	150	30	1.2	0.2
Pb-Bi	8.3	200	20	1.7	0.5
Nb-Ti	9.5	300	4	1.5	13.0
Nb-N	16.0	200	5	2.4	15.0
$PbMo_6S_8$	15.0	200	2	2.4	60.0
V_3Ga	15.0	90	2–3	2.3	23.0
V_3Si	16.0	60	3	2.3	20.0
Nb_3Sn	18.0	65	3	3.4	23.0
Nb_3Ge	23.0	90	3	3.7	38.0

* The values are only representative because the parameters for alloys and compounds depend on how the material is fabricated. The penetration depth $\lambda_{GL}(0)$ is given as the coefficient of the Ginzburg–Landau temperature dependence as $\lambda_{GL}(T) = \lambda_{GL}(0)(1 - T/T_c)^{-1/2}$; likewise for the coherence length where $\xi_{GL}(T) = \xi_{GL}(0)(1 - T/T_c)^{-1/2}$. The upper critical field $H_{c2,o}$ is given at zero temperature as well as the energy gap Δ_o.

From Delin, K.A. and Orlando, T.P., Superconductivity, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1225. Originally from R.J. Donnelly, "Cryogenics," in *Physics Vade Mecum,* H.L. Anderson, Ed., New York: American Institute of Physics, 1981. With permission.

Spontaneous Polarizations and Curie Temperatures for a Range of Ferroelectrics

Material	T_c(k)	P_s(cm-2)	T(k)
KH_2PO_4 (KDP)	123	0.053	96
Triglycine sulphate	322	0.028	293
Polyvinylidene fluoride (PVDF)	>453	0.060	293
DOBAMBC (liquid crystal)	359	$\sim 3 \times 10^{-5}$	354
$PbTiO_3$	763	0.760	293
$BaTiO_3$	393	0.260	296

From Whatmore, R.W., Pyroelectric materials and devices, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1230.

Pyroelectric Properties of Selected Materials

Material (Temperature)	Pyroelectric Coefficient P 10^{-4} cm^{-2} K^{-1}	Dielectric Properties (1 kHz) ϵ	Dielectric Properties (1 kHz) tanδ	Volume-Specific Heat c' 10^{6} Jm^{-3} K^{-1}	Thermal Conductivity K 10^{-7} m^{2} s^{-1}	F_v m^{2} C^{-1}	F_D 10^{-5} Pa$^{-1/2}$	F_{vid} 10^{6} sC^{-1}
TGS (35°C)	5.5	55	0.025	2.6	3.3	0.43	6.1	1.3
DTGS (40°C)	5.5	43	0.020	2.4	3.3	0.60	8.3	1.8
PVDF polymer	0.27	12	0.015	2.43	0.62	0.10	0.88	1.6
$LiTaO_3$ crystal	2.3	47	0.005	3.2	13.0	0.17	4.9	0.13
Modified PZ ceramic	3.8	290	0.003	2.5		0.06	5.8	
Modified PT ceramic	3.8	220	0.011	2.5		0.08	3.3	

PZ = $PbZrO_3$, PT = $PbTiO_3$.

From Whatmore, R.W., Pyroelectric materials and devices, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1233.

Electrical Properties of a Number of Representative Insulating Liquids

Liquid	Viscosity cSt (37.8°C)	Dielectric Constant (at 60 Hz, 25°C)	Dissipation Factor (at 60 Hz, 100°C)	Breakdown Strength, (kV cm^{-1})
Capacitor oil	21	2.2	0.001	>118
Pipe cable oil	170	2.15	0.001	>118
Self-contained cable oil	49.7	2.3	0.001	>118
Heavy cable oil	2365	2.23	0.001	>118
Transformer oil	9.75	2.25	0.001	>128
Alkyl benzene	6.0	2.1	0.0004	>138
Polybutene pipe cable oil	110 (SUS)	2.14 (at 1 MHz)	0.0003	>138
Polybutene capacitor oil	2200 (SUS at 100°C)	2.22 (at 1 MHz)	0.0005	>138
Silicone fluid	50	2.7	0.00015	>138
Castor oil	98 (100°C)	3.74	0.06	>138
$C_8F_{16}O$ fluorocarbon	0.64	1.86	<0.0005	>138

From Bartnikas, R., Dielectrics and insulators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1247. Originally from Bartnikas, R., Ed., *Engineering Dielectrics,* Vol. III, *Electrical Insulating Liquids,* Monograph 2, ASTM, Philadelphia, PA, 1994; Encyclopedia Issue, *Insul. Circuits,* June/July 1972.

Electrical and Physical Properties of Some Common Solid Insulating Materials

Material	Specific Gravity	Maximum Operating Temperature (°C)	Dielectric Constant 20°C 60 Hz	Dielectric Constant 20°C 1 kHz	Dielectric Constant 20°C 1 MHz	Dissipation Factor 20°C 60 Hz	Dissipation Factor 20°C 1 kHz	Dissipation Factor 20°C 1 MHz	AC Dielectric Strength (kV cm–1)
Alumina (Al_2O_3)	3.1–3.9	1950	8.5	8.5	8.5	1×10^{-3}	1×10^{-3}	1×10^{-3}	98–157
Porcelain (mullite)	2.3–2.5	1000	8.2	8.2	8.2	1.4×10^{-3}	5.7×10^{-4}	2×10^{-4}	94–157
Steatite $3MgO \cdot 4SiO_2 \cdot H_2O$	2.7–2.9	1000–1100	5.5	5.0	5.0	1.3×10^{-3}	4.5×10^{-4}	3.7×10^{-4}	200
Magnesium oxide (MgO)	3.57	<2800	9.65	9.65	9.69	$<3 \times 10^{-4}$	$<3 \times 10^{-4}$	$<3 \times 10^{-4}$	>2000
Glass (soda lime)	2.47	110–460	6.25	6.16	6.00	5.0×10^{-3}	4.2×10^{-3}	2.7×10^{-3}	4500
Mica ($KAl_2(OH)_2Si_3AlO_{10}$)	2.7–3.1	550	6.9	6.9	5.4	1.5×10^{-3}	2.0×10^{-4}	3.5×10^{-4}	3000–8200
SiO_2 film		<900		3.9			7×10^{-4}		1000–10,000
Si_3 N_4		<1000		12.7			$<1 \times 10^{-4}$		1000–10,000
Ta_2O_5	8.2	<1800		28			1×10^{-2}		
HfO_2		4700°F		35			1×10^{-2}		
Low-density PE	(density: 0.910–0.925 g cm^{-3})	70	2.3	2.3	2.3	2×10^{-4}	2×10^{-4}	2×10^{-4}	181–276
Medium-density PE	(density: 0.926–0.940 g cm^{-3})	70	2.3	2.3	2.3	2×10^{-4}	2×10^{-4}	2×10^{-4}	197–295
High-density PE	(density: 0.941–0.965 g cm^{-3})	70	2.35	2.35	2.35	2×10^{-4}	2×10^{-4}	2×10^{-4}	177–197

XLPE	(density: 0.92 g cm^{-3})	90	2.3		2.28	3×10^{-4}		4×10^{-4}	217
EPR	0.86	300–350°F		3.0–3.5		4×10^{-3}			354–413
Polypropylene	0.90	128–186	2.22–2.28	2.22–2.28	2.22–2.28	$2–3 \times 10^{-4}$	$2.5–3.0 \times 10^{-4}$	4.6×10^{-4}	295–314
PTFE	2.13–2.20	<327	2.0	2.0	2.0	$<2 \times 10^{-4}$	$<2 \times 10^{-4}$	$<2 \times 10^{-4}$	189
Glass-reinforced polyester premix	1.8–2.3	265	5.3–7.3		5.0−6.4	$1–4 \times 10^{-2}$		$0.8–2.2 \times 10^{-2}$	90.6–158
Thermoplastic polyester	1.31–1.58	250	3.3–3.8 (100 Hz)			$1.5–2.0 \times 10^{-3}$			232–295
Polyimide polyester	1.43–1.49	480°F		3.4 (100 kHz)			$1–5 \times 10^{-3}$ (100 kHz)		220
Polycarbonate	1.20	215	3.17		2.96	9×10^{-4}		1×10^{-2}	157
Epoxy (with mineral filler)	1.6–1.9	200 (decomposition temperature)	4.4–5.6	4.2–4.9	4.1–4.6	$1.1–8.3 \times 10^{-2}$	$0.19–1.4 \times 10^{-1}$	$0.13–1.4 \times 10^{-1}$	98.4–158
Epoxy (with silica filler)	1.6–2.0	200 (decomposition temperature)	3.2–4.5	3.2–4.0	3.0–3.8	$0.8–3.0 \times 10^{-2}$	$0.8–3.0 \times 10^{-2}$	$2–4 \times 10^{-2}$	158–217
Silicone rubber	1.1–1.5	700°F	3.3–4.0		3.1–3.7	$1.5–3.0 \times 10^{-2}$		$3.0–5.0 \times 10^{-3}$	158–197

From Bartnikas, R., Dielectrics and insulators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, pp. 1249–1250. Originally from Bartnikas, R. and Eichhorn, R.M., Eds., *Engineering Dielectrics,* Vol. IIA, *Electrical Properties of Solid Insulating Materials: Molecular Structure and Electrical Behavior,* STP 783, ASTM, Philadelphia, PA, 1983; Encyclopedia Issue, *Insul. Circuits,* June/July 1972.

Physical and Chemical Transduction Principles

Primary Signal	Secondary Signal: Mechanical	Thermal	Electrical	Magnetic	Radiant	Chemical
Mechanical	(Fluid) mechanical and acoustic effects (e.g., diaphragm, gravity balance, echo sounder)	Friction effects (e.g., friction calorimeter) Cooling effects (e.g., thermal flow meters)	Piezoelectricity Piezoresistivity Resistive, capacitive, and inductive effects	Magneto-mechanical effects (e.g., piezo-magnetic effect)	Photoelastic systems (stress-induced birefringence) Interferometers Sagnac effect Doppler effect	
Thermal	Thermal expansion (bimetal strip, liquid-in-glass and gas thermometers, resonant frequency) Radiometer effect (light mill)		Seebeck effect Thermoresistance Pyroelectricity Thermal (Johnson) noise		Thermooptical effects (e.g., in liquid crystals) Radiant emission	Reaction activation (e.g., thermal dissociation)
Electrical	Electrokinetic and electro-mechanical effects (e.g., piezoelectricity, electro-meter, Ampere's law)	Joule (resistive) heating Peltier effect	Charge collectors Langmuir probe	Biot-Savart's law	Electrooptical effects (e.g., Kerr effect) Pockel's effect Electroluminescence	Electrolysis Electromigration
Magnetic	Magnetomechanical effects (e.g., magnetorestriction, magnetometer)	Thermomagnetic effects (e.g., Righi-Leduc effect) Galvanomagnetic effects (e.g., Ettingshausen effect)	Thermomagnetic effects (e.g., Ettingshausen-Nernst effect) Galvanomagnetic effects (e.g., Hall effect, magnetoresistance)		Magnetooptical effects (e.g., Faraday effect) Cotton-Mouton effect	
Radiant	Radiation pressure	Bolometer thermopile	Photoelectric effects (e.g., photovoltaic effect, photoconductive effect)		Photorefractive effects Optical bistability	Photosynthesis, -dissociation
Chemical	Hygrometer Electrodeposition cell Photoacoustic effect	Calorimeter Thermal conductivity cell	Potentiometry Conductimetry Amperometry Flame ionization Volta effect Gas-sensitive field effect	Nuclear magnetic resonance	(Emission and absorption) spectroscopy Chemiluminiscence	

From Smith, R.L., Sensors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1256. Originally from T. Grandke and J. Hesse, Introduction, Vol. 1: *Fundamentals and General Aspects, Sensors: A Comprehensive Survey,* W. Gopel, J. Hesse, and J. H. Zemel, Eds., Weinheim, Germany: VCH, 1989. With permission.

Electrical Properties of Metals Used in Transmission Lines

Metal	Relative Conductivity (Copper = 100)	Electrical Resistivity at 20°C, $\Omega \cdot m$ (10^{-8})	Temperature Coefficient of Resistance (per °C)
Copper (HC, annealed)	100	1.724	0.0039
Copper (HC, hard-drawn)	97	1.777	0.0039
Aluminum (EC grade, 1/2 H-H)	61	2.826	0.0040
Mild steel	12	13.80	0.0045
Lead	8	21.4	0.0040

From Chen, M.-S., Alternating current overhead: Line parameters, models, standard voltages, insulators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1323.

Typical Synchronous Generator Parameters[a]

Parameter	Symbol	Round Rotor	Salient-Pole Rotor with Damper Windings
Synchronous reactance			
d-axis	X_d	1.0–2.5	1.0–2.0
q-axis	X_q	1.0–2.5	0.6–1.2
Transient reactance			
d-axis	X'_d	0.2–0.35	0.2–0.45
q-axis	X'_q	0.5–1.0	0.25–0.8
Subtransient reactance			
d-axis	X''_d	0.1–0.25	0.15–0.25
q-axis	X''_q	0.1–0.25	0.2–0.8
Time constants			
Transient			
Stator winding open-circuited	T'_{do}	4.5–13	3.0–8.0
Stator winding short-circuited	T'_d	1.0–1.5	1.5–2.0
Subtransient			
Stator winding short-circuited	T''_d	0.03–0.1	0.03–0.1

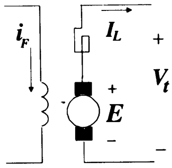
[a] Reactances are per unit, i.e., normalized quantities. Time constants are in seconds.

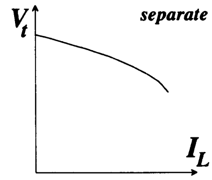
From Liu, C.-C., Vu, K.T., and Yu, Y., Generators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1451. Originally from M.A. Laughton and M.G. Say, eds., *Electrical Engineer's Reference Book,* Stoneham, Mass.: Butterworth, 1985.

Excitation Methods and Voltage Current Characteristics for DC Generators

Excitation Methods	Characteristics

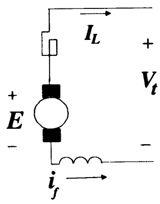
Separate

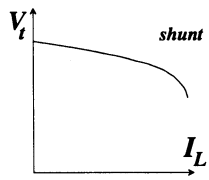




For low currents, the curve is nearly a straight line. As load current increases, the armature reaction becomes more severe and contributes to the nonlinear drop.

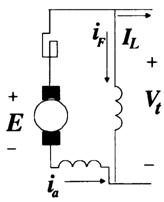
Series

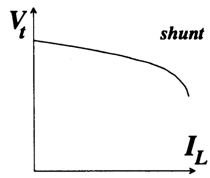




At no load, there is no field current, and voltage is due to the residual flux of the stator core. The voltage rises rapidly over the range of low currents, but the resistive drop soon becomes dominant.

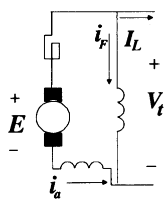
Shunt

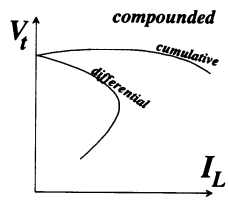




Voltage buildup depends on the residual flux. The shunt field resistance must be less than a critical value.

Compounded





There are two field windings. Depending on how they are set up, one may have *cumulative* if the two fields are additive, *differential* if the two fields are subtractive.

Cumulative: An increase in load current increases the resistive drop, yet creates more flux. At high currents, however, resistive drop becomes dominant.
Differential: An increase in load current not only increases the resistive drop, but also reduces the net flux. Voltage drops drastically.

From Liu, C.-C., Vu, K.T., and Yu, Y., Generators, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1455. Originally from S.J. Chapman, *Electric Machinery Fundamentals,* New York: McGraw-Hill, 1991.

Complex Envelope Functions for Various Types of Modulation

Type of Modulation	Mapping Functions $g[m]$	Corresponding Quadrature Modulation		Corresponding Amplitude and Phase Modulation		Linearity	Remarks
		$x(t)$	$y(t)$	$R(t)$	$\theta(t)$		
AM	$1 + m(t)$	$1 + m(t)$	0	$\lvert 1 + m(t) \rvert$	$\begin{cases} 0, & m(t) > -1 \\ 180^\circ, & m(t) < -1 \end{cases}$	L[b]	$m(t) > -1$ required for envelope detection.
DSB-SC	$m(t)$	$m(t)$	0	$\lvert m(t) \rvert$	$\begin{cases} 0, & m(t) > 0 \\ 180^\circ, & m(t) < 0 \end{cases}$	L	Coherent detection required.
PM	$e^{jD_p m(t)}$	$\cos[D_p m(t)]$	$\sin[D_p m(t)]$	1	$D_p m(t)$	NL	D_p is the phase deviation constant (radian/volts).
FM	$e^{jD_f \int_{-\infty}^{t} m(\sigma)d\sigma}$	$\cos\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$\sin\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	1	$D_f \int_{-\infty}^{t} m(\sigma)d\sigma$	NL	D_f is the frequency deviation constant (radian/volt-sec).
SSB-AM-SC[a]	$m(t) \pm j\hat{m}(t)$	$m(t)$	$\pm \hat{m}(t)$	$\sqrt{[m(t)]^2 + [\hat{m}(t)]^2}$	$\tan^{-1}[\pm \hat{m}(t)/m(t)]$	L	Coherent detection required.
SSB-PM[a]	$e^{jD_p[m(t) \pm j\hat{m}(t)]}$	$e^{\mp D_p \hat{m}(t)}\cos[D_p m(t)]$	$e^{\mp D_p \hat{m}(t)}\sin[D_p m(t)]$	$e^{\mp D_p \hat{m}(t)}$	$D_p m(t)$	NL	
SSB-FM[a]	$e^{jD_f \int_{-\infty}^{t} [m(\sigma) \pm j\hat{m}(\sigma)]d\sigma}$	$e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma}\cos\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma}\sin\left[D_f \int_{-\infty}^{t} m(\sigma)d\sigma\right]$	$e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma}$	$D_f \int_{-\infty}^{t} m(\sigma)d\sigma$	NL	
SSB-EV[a]	$e^{\{\ln[1 + m(t)] \pm j\hat{\ln}[1 + m(t)]\}}$	$[1 + m(t)] \cos \{\hat{\ln}[1 + m(t)]\}$	$\pm[1 + m(t)]\sin\{\hat{\ln}[1 + m(t)]\}$	$1 + m(t)$	$\pm\hat{\ln}[1 + m(t)]$	NL	$m(t) > -1$ is required so that the ln will have a real value.
SSB-SQ[a]	$e^{(1/2)\{\ln[1 + m(t)] \pm j\hat{\ln}[1 + m(t)]\}}$	$\sqrt{1 + m(t)} \cos\left\{\frac{1}{2}\hat{\ln}[1 = m(t)]\right\}$	$\pm\sqrt{1 + m(t)} \sin\left\{\frac{1}{2}\hat{\ln}[1 + m(t)]\right\}$	$\sqrt{1 + m(t)}$	$\pm \frac{1}{2}\hat{\ln}[1 + m(t)]$	NL	$m(t) > -1$ is required so that the ln will have a real value.
QM	$m_1(t) + jm_2(t)$	$m_1(t)$	$m_2(t)$	$\sqrt{m_1^2(t) + m_2^2(t)}$	$\tan^{-1}[m_2(t)/m_1(t)]$	L	Used in NTSC color television: requires coherent detection.

L = linear, NL = nonlinear, $[\hat{\cdot}]$ is the Hilbert transform (i.e., –90° phase-shifted version) of $[\cdot]$. The Hilbert transform is $\hat{x}(t) \triangleq x(t) * \frac{1}{\pi t} = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{x(\lambda)}{t - \lambda} d\lambda$

[a] Use upper signs for upper sideband signals and lower signs for lower sideband signals.

[b] In the strict sense, AM signals are not linear because the carrier term does not satisfy the linearity (superposition) condition.

From Dorf, R.C. and Wan, Z., Modulation and demodulation, in *The Electrical Engineering Handbook*, 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1505. Orignally from L. W. Couch, *Digital and Analog Communication Systems*, New York: Macmillan, 1990. With permission.

Protected Service Signal Intensities for Standard Broadcasting (AM)

Class of Station	Power (kW)	Class of Channel Used	Signal Strength Contour of Area Protected from Objectionable Interference* (μV/m)		Permissible Interfering Signal	
			Day†	Night	Day†	Night‡
A	10–50	Clear	SC 100 AC 500	SC 500 50% SW AC 500 GW	SC 5 AC 250	SC 25 AC 250
B	0.25–50	Clear Regional	500	2000†	25 AC 250	25 250
C	0.25–1	Local	500	Not precise§	SC 25	Not precise
D	0.25–50	Clear Regional	500	Not precise	SC 25 AC 250	Not precise

* When a station is already limited by interference from other stations to a contour of higher value than that normally protected for its class, this higher-value contour shall be the established protection standard for such station. Changes proposed by Class A and B stations shall be required to comply with the following restrictions. Those interferers that contribute to another station's RSS using the 50% exclusion method are required to reduce their contribution to that RSS by 10%. Those lesser interferers that contribute to a station's RSS using the 25% exclusion method but do not contribute to that station's RSS using the 50% exclusion method may make changes not to exceed their present contribution. Interferers not included in a station's RSS using the 25% exclusion method are permitted to increase radiation as long as the 25% exclusion threshold is not equaled or exceeded. In no case will a reduction be required that would result in a contributing value that is below the pertinent value specified in the table.

† Groundwave.

‡ Skywave field strength for 10% or more of the time. For Alaska, Class SC is limited to 5 μV/m.

§ During nighttime hours, Class C stations in the contiguous 48 states may treat all Class B stations assigned to 1230, 1240, 1340, 1400, 1450, and 1490 kHz in Alaska, Hawaii, Puerto Rico and the U.S. Virgin Islands as if they were Class C stations.

Note: SC = same channel; AC = adjacent channel; SW = skywave; GW = groundwave; RSS = root of sum squares.

From Lindsey III, J.F. and Doelizsch, D.F., Radio broadcasting, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1515. Originally from FCC Rules and Regulations, Revised 1991; vol. III, pt. 73.182(a).

Coding Gains with BPSK or QPSK

Coding Technique Used	Coding Gain (dB) at 10^{-5} BER	Coding Gain (dB) at 10^{-8} BER	Data Rate Capability
Ideal coding	11.2	13.6	
Concatenated Reed–Solomon and convolution (Viterbi decoding)	6.5–7.5	8.5–9.5	Moderate
Convolutional with sequential decoding (soft decisions)	6.0–7.0	8.0–9.0	Moderate
Block codes (soft decisions)	5.0–6.0	6.5–7.5	Moderate
Concatenated Reed–Solomon and short block	4.5–5.5	6.5–7.5	Very high
Convolutional with Viterbi decoding	4.0–5.5	5.0–6.5	High
Convolutional with sequential decoding (hard decisions)	4.0–5.0	6.0–7.0	High
Block codes (hard decisions)	3.0–4.0	4.5–5.5	High
Block codes with threshold decoding	2.0–4.0	3.5–5.5	High
Convolutional with threshold decoding	1.5–3.0	2.5–4.0	Very high

BPSK: modulation technique—binary phase-shift keying; QPSK: modulation technique—quadrature phase-shift keying; BER: bit error rate.

From Dorf, R.C. and Wan, Z., Error control coding, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1554. Originally from V.K. Bhargava, "Forward error correction schemes for digital communications," *IEEE Communication Magazine,* 21, 11–19, © 1983 IEEE. With permission.

Comparison of Orbit and Link Parameters for LEO, MEO, and GEO for the Particular Case of Circular Orbits (eccentricity, *e*, = 0) and for Elevation Angle (*el* = 10°)

Orbit	LEO	MEO/ICO	GEO
Example system	Iridium®	ICO-P	INTELSAT
Inclination, i (deg.)	86.4	±45	0
Altitude, h (km)	780	10,400	35,786
Semi-major axis radius, a (km)	7159	16,778	42,164
Orbit period (minutes)	100.5	360.5	1436.1
$(r_e + h)/r_e$	1.1222	2.6305	6.6107
Earth central angle, γ (deg.)	18.658	58.015	71.433
Nadir angle, θ (deg.)	61.3	22	8.6
Nadir spread factor 10 log($4\pi h^2$ (dB m^2))	128.8	151.3	162.1
Slant range, r_s (km)	2325	14,450	40,586
One-way time delay (ms)	2.6	51.8	139.1
Maximum spread factor			
10 log($4\pi r_s^2$ (dB m^2))	138.3	154.2	163.2
20 log(r_s/h (dB))	9.5	2.9	1.1
Ground coverage area (km^2)	13.433 × 106	120.2 × 106	174.2 × 106
Fraction of earth area	0.026	0.235	0.34

Note: earth radius, r_e, (km) = 6378.14; earth surface area, a_e, (km^2) = 511.2 × 10^6; elevation angle, *el* (degrees) = 10.

From DiFonzo, D.F., Satellites and aerospace, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1701.

Partial List of Satellite Frequency Allocations

Band	Uplink	Downlink	Satellite Service
VHF		0.137–0.138	Mobile
VHF	0.3120–0.315	0.387–0.390	Mobile
L-Band		1.492–1.525	Mobile
	1.610–1.6138		Mobile, radio astronomy
	1.613.8–1.6265	1.6138–1.6265	Mobile LEO
	1.6265–1.6605	1.525–1.545	Mobile
		1.575	Global positioning system
		1.227	GPS
S-Band	1.980–2.010	2.170–2.200	MSS (available Jan. 1, 2000)
	1.980–1.990	2.165–2.200	(proposed for U.S. in 2000)
	2.110–2.120	2.290–2.300	Deep-space research
		2.4835–2.500	Mobile
C-Band	5.85–7.075	3.4–4.2	Fixed (FSS)
	7.250–7.300	4.5–4.8	FSS
X-Band	7.9–8.4	7.25–7.75	FSS
Ku-Band	12.75–13.25	10.7–12.2	FSS
	14.0–14.8	12.2–12.7	Direct Broadcast (BSS) (U.S.)
Ka-Band		17.3–17.7	FSS (BSS in U.S.)
			22.55–23.55 Intersatellite
			24.45–24.75 Intersatellite
			25.25–27.5 Intersatellite
	27–31	17–21	FSS
Q	42.5–43.5, 47.2–50.2	37.5–40.5	FSS, MSS
	50.4–51.4		Fixed
		40.5–42.5	Broadcast Satellite
V	54.24–58.2–		Intersatellite
	59–64		Intersatellite

Note: Frequencies in GHz. Allocations are not always global and may differ from region to region in all or subsets of the allocated bands.

From DiFonzo, D.F., Satellites and aerospace, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1703. Originally from Final Acts of the World Administrative Radio Conference (WARC-92), Malaga-Torremolinos, 1992; 1995 World Radiocommunication Conference (WRC-95).

Specifications of TDMA and CDMA Systems

TDMA		CDMA	
Bandwidth per channel	30 kHz	Bandwidth per channel	1.23 MHz
Time slots	3	Speech coder	8 kbps(max.)—a variable rate vocoder
Modulation	π/4-DQPSK	Forward radio channels	Pilot (1) sync (1), paging (7), traffic channels (55), total 64 channels
Speech coder	8 kbps—VSELP code (vector sum excited LPC*)		
Channel coding	Rate 1/2 convolutional (13 kbps)	Reverse radio channels	Access (9), traffic channels (55)
Total transmit rate	48 kbps per channel	Power control	Forward, reverse
Equalizer	Up to 40 μs	Diversity	Rake receiver

* LPC = linear predictive code.

From Lee, W.C.Y., Mobile radio and cellular communications, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1710.

Switching Algebra Summary

(P1) $XY = YX$	(S1) $X + Y = Y + X$	Commutativity
(P2) $X(YZ) = (XY)Z$	(S2) $X + (Y + Z) = (X + Y) + Z$	Associativity
(P3) $XX = X$	(S3) $X + X = X$	Idempotency
(P4) $X(X + Y) = X$	(S4) $X + XY = X$	Absorption
(P5) $X(Y + Z) = XY + XZ$	(S5) $X + YZ = (X + Y)(X + Z)$	Distributivity
(P6) $X\overline{X} = 0$	(S6) $X + \overline{X} = 1$	Complementarity
(C1) $\overline{\overline{X}} = X$		Involution
(P7) $\overline{XY} = \overline{X} + \overline{Y}$	(S7) $\overline{X + Y} = \overline{X}\,\overline{Y}$	De Morgan's
(P8) $X(\overline{X} + Y) = XY$	(S8) $X + \overline{X}Y = X + Y$	
(B1) $\overline{1} = 0$		
(P10) $X \cdot 0 = 0$	(S10) $X + 1 = 1$	
(P11) $X \cdot 1 = X$	(S11) $X + 0 = X$	
(P13) $(X + Y)(Y + Z)(\overline{X} + Z) = (X + Y)(\overline{X} + Z)$	(S13) $XY + YZ + \overline{X}Z = XY + \overline{X}Z$	Consensus

From Preparata, F.P., Combinational networks and switching algebra, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1858.

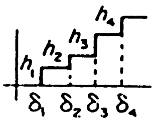
Binary-to-Decimal Conversion

Two-Bit Binary	Decimal Value	Three-Bit Binary	Decimal Value	Four-Bit Binary	Decimal Value	Five-Bit Binary	Decimal Value	Six-Bit Binary	Decimal Value
00	0	000	0	0000	0	10000	16	100000	32
01	1	001	1	0001	1	10001	17	100001	33
10	2	010	2	0010	2	10010	18	100010	34
11	3	011	3	0011	3	10011	19	100011	35
		100	4	0100	4	10100	20	100100	36
		101	5	0101	5	10101	21	100101	37
		110	6	0110	6	10110	22	100110	38
		111	7	0111	7	10111	23	100111	39
				1000	8	11000	24	101000	40
				1001	9	11001	25	101001	41
				1010	10	11010	26	101010	42
				1011	11	11011	27	101011	43
				1100	12	11100	28	101100	44
				1101	13	11101	29	101101	45
				1110	14	11110	30	101110	46
				1111	15	11111	31	101111	47

From Tinder, R.F., Number systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 1993.

DFs of Single-Valued Nonlinearities

General quantizer



$a < \delta_1$ — $N_p = 0$

$\delta_{M+1} > a > \delta_M$ — $$N_p = \left(4/\alpha^2\pi\right)\sum_{m=1}^{M} h_m\left(a^2 - \delta_m^2\right)^{1/2}$$

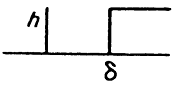
Uniform quantizer
$h_1 = h_2 = \cdots h$
$\delta_m = (2m - 1)\delta/2$

$a < \delta$ — $N_p = 0$

$(2M + 1)\delta > a > (2M - 1)\delta$ — $$N_p = \left(4h/a^2\pi\right)\sum_{n=1}^{M}\left(a^2 - n^2\delta^2\right)^{1/2}$$

$n = (2m - 1)/2$

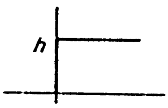
Relay with dead zone



$a < \delta$ — $N_p = 0$

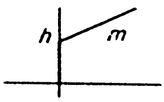
$a > \delta$ — $N_p = 4h(a^2 - \delta^2)^{1/2}/a^2\pi$

Ideal relay



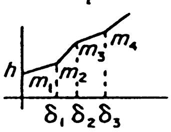
$N_p = 4h/a\pi$

Preload



$N_p = (4h/a\pi) + m$

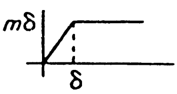
General piecewise linear



$a < \delta_1$ — $N_p = (4h/a\pi) + m_1$

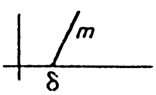
$\delta_{M+1} > \alpha > \delta_M$ — $$N_p = (4h/a\pi) + m_{M+1} + \sum_{i=1}^{M}\left(m_j - m_{j+1}\right)N_i\left(\delta_j/a\right)$$

Ideal saturation



$N_p = mN_s(\delta/a)$

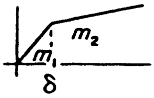
Dead zone



$N_p = m[1 - N_s(\delta/a)$

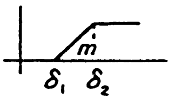
DFs of Single-Valued Nonlinearities (continued)

Gain changing nonlinearity

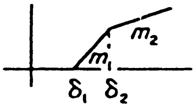


$N_p = (m_1 - m_2)N_s(\delta/a) + m_2$

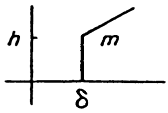
Saturation with dead zone



$N_p = m[N_s(\delta_2/a) - N_s(\delta_1/a)]$

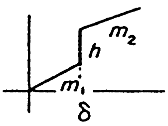


$N_p = -m_1 N_s(\delta_1/a) + (m_1 - m_2)N_s(\delta_2/a) + m_2$



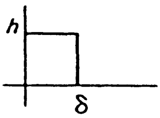
$a < \delta$ $N_p = 0$

$a > \delta$ $N_p = 4h(a^2 - \delta^2)^{1/2}/a_2\pi + m - mN_s(\delta/a)$



$a < \delta$ $N_p = m_1$

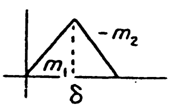
$a > \delta$ $N_p = (m_1 - m_2)N_s(\delta/a) + m_2 + 4h(a^2 - \delta^2)^{1/2}/a^2\pi$



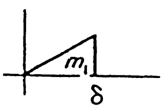
$a < \delta$ $N_p = 4h/a\pi$

$a > \delta$ $N_p = 4h/[a - (a^2 - \delta^2)^{1/2}]/a^2\pi$

Limited field of view



$N_p = (m_1 + m_2)N_s(\delta/a) - m_2 N_s[(m_1 + m_2)\delta/m_2 a]$



$a < \delta$ $N_p = m_1$

$a > \delta$ $N_p = m_1 N_s(\delta/a) - 4m_1\delta(a^2 - \delta^2)^{1/2}/a^2\pi$

$y = x^m$

$m > -2$ Γ is the gamma function

$$N_p = \frac{\Gamma(m+1)a^{m-1}}{2^{m-1}\Gamma[(3+m)/2]\Gamma[(1+m)/2]}$$

$$= \frac{2}{\sqrt{\pi}}\frac{\Gamma[(m+2)/2]a^{m-1}}{\Gamma[(m+3)/2]}$$

From Atherton, D.P., Nonlinear control systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, pp. 2318–2319.

Illuminance Categories and Illuminance Values for Generic Types of Activities in Interiors

Type of Activity	Illuminance Category	Ranges of Illuminances		Reference Work-Plane
		Lux	Footcandles	
Public spaces with dark surroundings	A	20–30–50	2–3–5	General lighting throughout spaces
Simple orientation for short temporary visits	B	50–75–100	5–7.5–10	
Working spaces where visual tasks are only occasionally performed	C	100–150–200	10–15–20	
Performance of visual tasks of high contrast or large size	D	200–300–500	20–30–50	Illuminance on task
Performance of visual tasks of medium contrast or small size	E	500–750–1,000	50–75–100	
Performance of visual tasks of low contrast or very small size	F	1,000–1,500–2,000	100–150–200	
Performance of visual tasks of low contrast and very small size over a prolonged period	G	2,000–3,000–5,000	200–300–500	Illuminance on task, obtained by a combi- nation of general and local (supplementary lighting)
Performance of very prolonged and exacting visual tasks	H	5,000–7,500–10,000	500–750–1,000	
Performance of very special visual tasks of extremely low contrast and small size	I	10,000–15,000–20,000	1,000–1,500–2,000	

From Chen, K., Industrial illuminating systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2449. Originally from *IES Lighting Handbook, Application Volume*.

Representative Transducers

Measurand	Transducer	Operating Principles
Displacement (Length)	Resistive Capacitive Inductive	Change in resistance, capacitance, or inductance caused by linear or angular displacement of transducer element
Force	Strain gage	Resistance, piezoresistivity
Temperature	Thermistor	Resistance
	Thermocouple	Peltier, seebeck effect
Pressure	Diaphragm	Diaphragm motion sensed by a displacement technique.
Flow	Differential pressure	Pressure drop across restriction
	Turbine	Angular velocity proportional to flow rate

From Schmalzel, J.L., Instruments, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2470.

Worldwide Radio Navigation Aids

System	Frequency		Number of Stations	Number of Users in 1996			
	Hz	Band		Air	Marine	Space	Land
Omega	10–13 kHz	VLF	8	15,000	10,000	0	0
Loran-C/Chaika	100 kHz	LF	50	120,000	550,000	0	25,000
Decca	70–130 kHz	LF	150	2,000	20,000	0	0
Beacons*	200–1600 kHz	MF	4000	130,000	500,000	0	0
Instrument Landing System (ILS)*	108–112 MHz 329–335 MHz	VHF UHF	1500	150,000	0	0	0
VOR*	108–118 MHz	VHF	1500	180,000	0	0	0
SARSAT/COSPAS	121.5 MHz 243,406 MHz	VHF UHF	5 satellites	200,000	200,000	0	100,000
Transit	150, 400 MHz	VHF	7 satellites	0	0	0	0
PLRS	420–450 MHz	UHF	None	0	0	0	2,000
JTIDS	960–1213 MHz	L	None	500	0	0	0
DME*	962–1213 MHz	L	1500	90,000	0	4	0
Tacan*	962–1213 MHz	L	850	15,000	0	4	0
Secondary Surveillance Radar (SSR)*	1030, 1090 MHz	L	800	250,000	0	0	0
Identification Friend or Foe (IFF)							
GPS-GLONASS	1227, 1575 MHz	L	24 + 24 satellites	120,000	275,000	4	125,000
Satellite Control Network (SCN)	1760–1850 MHz 2200–2300 MHz	S S	10	0	0	200	0
Spaceflight Tracking and Data Network (STDN)	2025–2150 MHz 2200–2300 MHz	S	3 satellites 10 ground	0	0	50	0
Radar Altimeter	4200 MHz	C	None	20,000	0	0	0
MLS*	5031–5091 MHz	C	30	100	0	0	0
FPQ-6, FPQ-16 radar	5.4–5.9 GHz	C	10	0	0	0	0
Weather/map radar	10 GHz	X	None	10,000	0	0	0
Shuttle rendezvous radar	13.9 GHz	Ku	None	0	0	4	0
Airborne Doppler radar	13–16 GHz	Ku	None	20,000	0	0	0
SPN-41 carrier-landing monitor	15 GHz	Ku	25	1600	0	0	0
SPN-42/46 carrier-landing radar	33 GHz	Ka	25	1600	0	0	0

* Standardized by International Civil Aviation Organization.

From Kayton, M., Navigation systems, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2482.

Classifications of Chemical Biomedical Sensors

1. Electrochemical
   a. Amperometric
   b. Potentiometric
   c. Coulometric
2. Optical
   a. Colorimetric
   b. Emission and absorption spectroscopy
   c. Fluorescence
   d. Chemiluminescence
3. Thermal methods
   a. Calorimetry
   b. Thermoconductivity
4. Nuclear magnetic resonance

From Neuman, M., Biomedical sensors, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2587.

Approximate Ultrasonic Attenuation Coefficient, Speed, and Characteristic Impedance for Water and Selected Tissues at 3.5 MHz

Tissue	Attenuation Coefficient (m^{-1})	Speed (m/s)	Characteristic Impedance (10^6 Pa s/m)
Water	0.2	1520	1.50
Amniotic fluid	0.7	1510	1.51
Blood	7	1550	1.60
Liver	35	1580	1.74
Muscle	50	1560	1.72
Bone	800	3360	5.70
Lung	1000	340	0.25

From Frizzell, L.A., Ultrasound, in *The Electrical Engineering Handbook,* 2nd ed., Dorf, R.C., Ed., CRC Press, Boca Raton, FL, 1998, p. 2623.

Parasitics in Various Electronic Packages

Package Type	Parasitic Capacitance, pF	Parasitic Inductance, nH
Flip chip	0.1	0.01
Chip on board/wire bond	0.5	1–2
Pin grid array	1	2
Quad flat pack	1	1–6
Through-hole DIP	3	8–20

From Blackwell, G.R., Direct chip attach, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **4**-5.

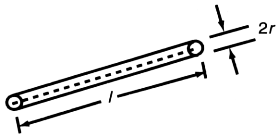
Wiring Board Material Properties

Material	ε_r'	$\varepsilon_r''/\varepsilon_r'$	CTE (× 10^{-6}/°C) x, y	CTE (× 10^{-6}/°C) z	T_g, °C
FR-4 epoxy-glass	4.0–5.0	0.02–0.03	16–20	60–90	125–135
Polyimide-glass	3.9–4.5	0.005–0.02	12–14	60	>260
Teflon®	2.1	0.0004–0.0005	70–120		—
Benzocyclobutene	2.6	0.0004	35–60		>350
High-temperature one-component epoxy-glass	4.45–4.45	0.02–0.022			170–180
Cyanate ester-glass	3.5–3.9	0.003–0.007			240–250
Ceramic	~10.0	0.0005	6–7		—
Copper	—	—	17		—
Copper/invar/copper	—	—	3–6		—

From Blackwell, G.R., Circuit boards, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **5**-3.

Interconnect Models

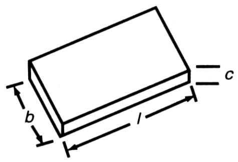
Interconnect type — **Model**



Round wire

$$L \cong 0.002l\left[\ln\left(\frac{2l}{r} - 0.75\right)\right], \mu H; l > r$$

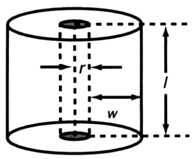
l, r in cm.



Straight rectangular bar or ribbon

$$L \cong 0.002l\left[\ln\frac{2l}{b+c} + 0.5 + 0.2235\frac{b+c}{l}\right], \mu H$$

b, c, l in cm.



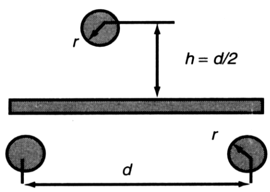
Via

$$L = 0.002l\left[\ln\frac{2l}{r+W} - 1 + \xi\right], \mu H$$

where

$$\xi = 0.25\left[\cos\left(\frac{r}{r+W}\frac{\pi}{2}\right) - 0.07\sin\left(\frac{r}{r+W}\pi\right)\right]$$

l, r, W in cm.



Round wire over a ground plane and parallel round wires

$$Z_0 = \frac{120}{\sqrt{\varepsilon_r}}\cosh^{-1}\frac{d}{2r}, \text{ohm}$$
$$= \frac{120}{\sqrt{\varepsilon_r}}\ln\frac{d}{r}, \text{ohm}; d \gg r$$

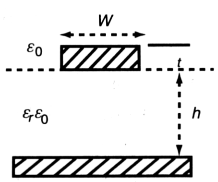
$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{10h}{W_e}\right]^{-a.b}$$

where

$$\frac{W_e}{h} = \frac{W}{h} + \frac{1.25}{\pi}\frac{t}{h}\left[1 + \ln\frac{2[h^4 + (2\pi W)^4]^{0.25}}{t}\right]$$

$$a = 1 + \frac{1}{49}\ln\left\{\frac{\left[\left(\frac{W_e}{h}\right)^4 + \left(\frac{W_e}{52h}\right)^2\right]}{\left[\left(\frac{W_e}{h}\right)^4 + 0.432\right]}\right\} + \frac{1}{18.7}\ln\left[1 + \left(\frac{W_e}{18.1h}\right)^3\right]$$

$$b = 0.564\left[\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right]^{0.053}$$

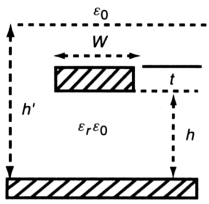
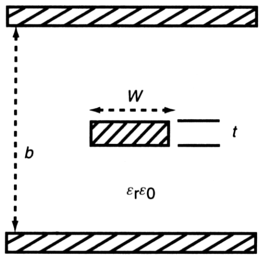
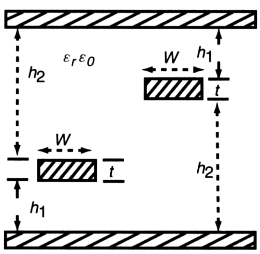


Microstrip

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{reff}}}\ln\left[\frac{F_1 h}{W_e} + \sqrt{1 + \left(\frac{2h}{W_e}\right)^2}\right]$$

with $F_1 = 6 + (2\pi - 6)e^{-\left(30.666\frac{h}{W_e}\right)^{0.7528}}$

Interconnect Models (continued)

Interconnect type	Model
 Buried microstrip	Z_0 same expression as microstrip with $\varepsilon_{r\text{eff}} = \varepsilon_r \left[1 - e^{K \frac{h'}{h}}\right]$ where $K = \ln \left\{ \dfrac{1}{\left[1 - \dfrac{\varepsilon_{r\text{eff}}(h' = h)}{\varepsilon_r}\right]} \right\}$ $[\varepsilon_{r\text{eff}}(h' = h)]$ is given by the microstrip formula
 Stripline	$\varepsilon_{r\text{eff}} = \varepsilon_r$ $Z_0 = \dfrac{30}{\sqrt{\varepsilon_{r\text{eff}}}} \ln\left[1 + \dfrac{4}{\pi W_n}\left(\dfrac{8}{\pi W_n} + \sqrt{\dfrac{8}{\pi W_n} + 6.27}\right)\right]$ where $W_n = \dfrac{W}{b - t} + \dfrac{t_n}{\pi(1 - t_n)}$ $\times \left\{1 - \dfrac{1}{2} \ln\left[\left(\dfrac{t_n}{2 - t_n}\right)^2 + \left(\dfrac{0.0796 t_n}{1.1 t_n + \dfrac{W}{b}}\right)^m\right]\right\}$ $t_n = \dfrac{t}{b}$ and $m = b\left(\dfrac{1 - t_n}{3 - t_n}\right)$
 Asymmetric and dual striplines	$Z_0 = \dfrac{80Y}{0.918\sqrt{\varepsilon_r}} \ln\left[\dfrac{3.8h_1 + 1.9t}{0.8W + t}\right]$ $Y = \left[1.0636 + 0.33136\dfrac{h_1}{h_2} - 1.9007\left(\dfrac{h_1}{h_2}\right)^3\right]$

From Blackwell, G.R., Circuit boards, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **5**-13 to **5**-14.

Dielectric Constants and Wave Velocities within Various PCB Materials

Material	ε_r (at 30 MHz)	Velocity (in/ns)	Velocity (ps/in)
Air	1.0	11.76	85.0
PTFE/glass (Teflon™)	2.2	7.95	125.8
RO 2800	2.9	6.95	143.9
CE/custom ply (Canide ester)	3.0	6.86	145.8
BT/custom ply (Beta-triazine)	3.3	6.50	153.8
CE/glass	3.7	6.12	163.4
Silicon dioxide	3.9	5.97	167.5
BT/glass	4.0	5.88	170.1
Polyimide/glass	4.1	5.82	171.8
FR–4 glass	4.5	5.87	170.4
Glass cloth	6.0	4.70	212.8
Alumina	9.0	3.90	256.4

Note: Values measured at TDR frequencies using velocity techniques.

Values were not measured at 1 MHz, which provides faster velocity values. Units for velocity differ due to scaling and are presented in this format for ease of presentation.

From Montrose, M.I., EMC and printed circuit board design, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **6**-40. Originally from IPC–2141, *Controlled Impedance Circuit Boards and High Speed Logic Design,* Institute for Interconnecting and Packaging Electronics Circuits. © 1996. Reprinted with permission.

Wire Ampacity and Size

AWG wire size	Resistance, Ω per 1000 ft	Ampacity for low-temperature insulation	Ampacity for high-temperature insulation	Bare wire diameter mm (in)
30	100	2	4	0.254 (0.0100)
28	60	3	6	0.320 (0.0126)
26	40	4	7	0.404 (0.0159)
24	25	6	10	0.511 (0.0201)
22	14	8	13	0.643 (0.0253)
20	10	10	17	0.810 (0.0319)
18	6	15	24	1.024 (0.0403)

Note: Ω/1000 ft is approximate. Exact value depends on whether the conductor is solid or stranded, and if stranded, the type of stranding. Consult the manufacturers' data sheets for exact values.

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-4.

Parameters for Multimode and Single-Mode Fiber

Parameter	Multimode (62.5/125 μm)	Dispersion-Unshifted Single-Mode
Core size	62.5 ± 3.0 μm	8.3 μm (typical)
Mode field diameter	—	8.8–9.3 μm (typical)
Numerical aperture	0.275 ± 0.015	0.13 (typical)
Cladding diameter	125.0 ± 2.0 μm	125.0 ± 1.0 μm
Attenuation	≤3.5 dB/km at 850 nm	≤0.5 dB/km at 1310 nm
	≤1.5 dB/km at 1300 nm	≤0.4 dB/km at 1550 nm
Bandwidth	≥160 MHz·km at 850 nm	—
	≥500 MHz·km at 1300 nm	
Dispersion	—	≤3.5 ps/nm·km for 1285–1330 nm

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-24.

Standard Optical Cable Color Coding

Unit or Fiber	Color	Unit or Fiber	Color
1	Blue	7	Red
2	Orange	8	Black
3	Green	9	Yellow
4	Brown	10	Violet
5	Slate	11	Rose
6	White	12	Aqua

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-30.

Common Tests for Optical Fiber

Test	FOTP	Purpose
Core diameter	FOTP–43 and –58	Determine the size of the core in a multimode fiber to ensure compatibility with other fibers of the same core size as well as with end equipment.
Mode field diameter	FOTP–167	Measure of the spot size of light propagating in a single-mode fiber to ensure compatibility with other fibers of similar core size as well as with end equipment. Differences in mode field diameters of two fibers being spliced together can affect splice loss.
Cladding diameter	FOTP–176	Determine the size of the cladding. The consistency of cladding diameter can affect connector and mechanical splice performance.
Core–clad concentricity	FOTP–176	Distance between the center of the core and the center of the cladding. High values can affect splice and connector losses.
Core noncircularity	FOTP–176	Measures the roundness of multimode cores. High values can have a slight effect on splice and connector losses.
Cladding noncircularity	FOTP–176	Measures the roundness of the cladding. High values can have a slight effect on splice and connector losses.
Fiber cutoff wavelength	FOTP–80	Measures the minimum wavelength at which a single-mode fiber will support the propagation of only one mode. If the system wavelength is below the cutoff wavelength, multimode operation may occur introducing modal dispersion and higher attenuation. The difference in fiber and cable cutoff wavelength is due to the deployment of fiber during the test. Cabling can shift the cutoff wavelength to a lower value.
Cable cutoff wavelength	FOTP–170	
Curl	FOTP–111 (underdevelopment)	Measures the curvature of a short length of fiber in an unsupported condition. Excessive curl can affect splice loss in passive alignment fusion splicers such as mass fusion splicers.
Coating diameter	FOTP–173	Measures the outside diameter of a coated fiber. Out of spec values can affect cable manufacturing and potentially cable performance.
Numerical aperture	FOTP–47 and –177	Measures the numerical aperture of a fiber. Ensures compatibility with other fibers as well as end equipment.
Proof test	FOTP–31	Ensures the minimum strength of a fiber. Every fiber is normally subjected to the proof test.
Attenuation coefficient	FOTP–61 and –78	Measured by the fiber and cable manufacturers and reported to the customer in units of dB/km.
Bandwidth	FOTP–30 and –5	Measured by the fiber manufacturer and reported to the customer by the cable manufacturer in units of MHz·km.

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-47.

Common Tests for Optical Cable Design

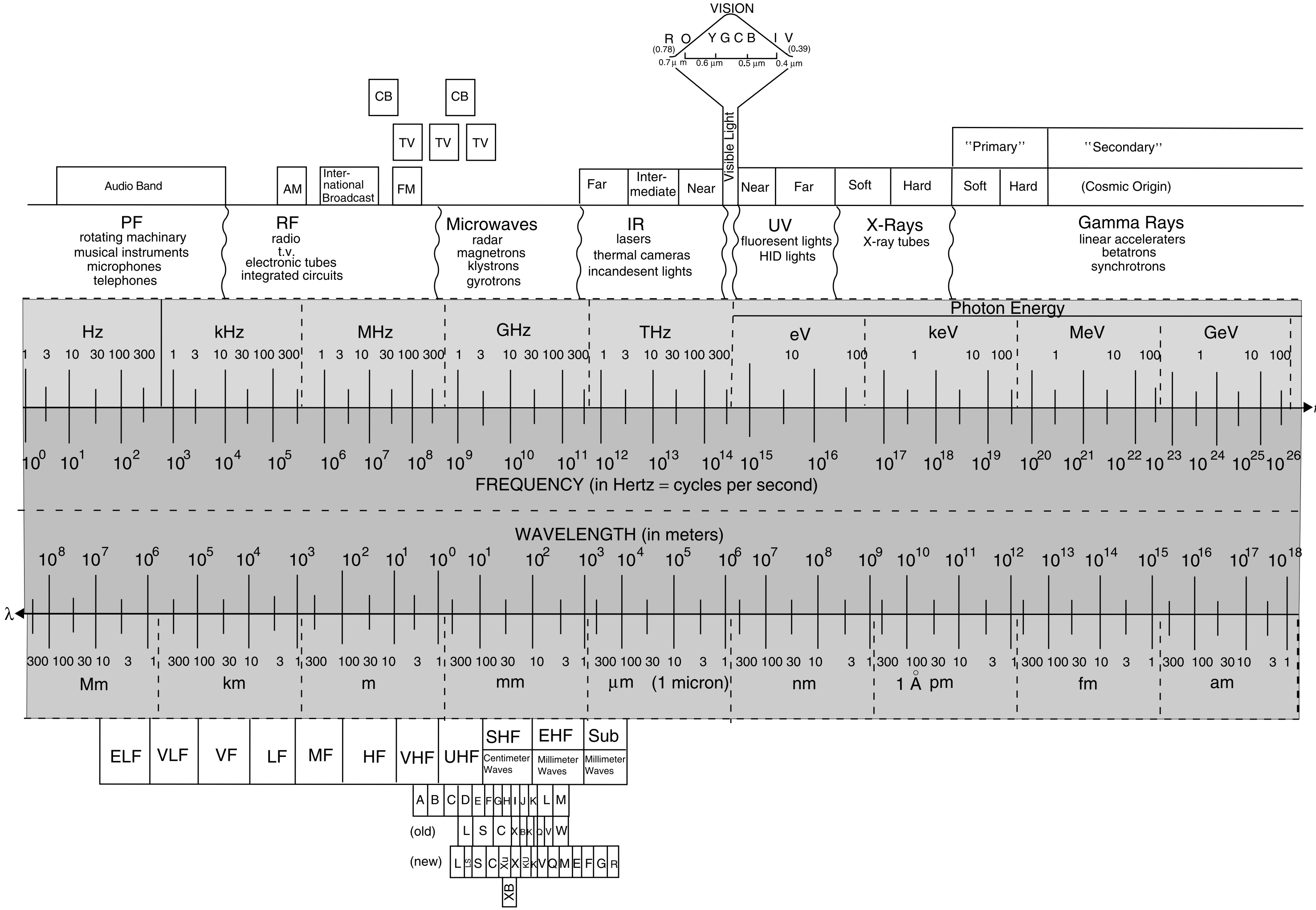
Test	FOTP	Purpose
Temperature cycling	FOTP–3	Simulates environmental conditions once the cable is deployed.
Impact	FOTP–25	Simulates an object being dropped on the cable for a sudden and brief impact.
Tensile	FOTP–33	Measures the performance of the cable at its rated tensile load simulating installation by pulling.
Compressive load	FOTP–41	Measures cable performance while under a compressive or crushing force.
Cable twist	FOTP–85	Measures the ability of the cable to perform when under a twist condition.
Cycle flex or bend	FOTP–104	Measures the ability of the cable to perform even when subjected to a bend, and withstand repeated bending during installation.
Water penetration	FOTP–82	Measures the ability of an outdoor cable to prevent the ingress of water along the length of the cable.
Filling and flooding compound flow	FOTP–81	Measures the resistance to flow of compound flow filling and flooding compounds at elevated temperatures.

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-47.

Cable Interconnects

Cable Designation	Nominal Z_0	V_p	Diameter, in	Nominal Atten. at 50 MHz, dB/100 ft	Nominal Atten. at 200 MHz, dB/100 ft	Nominal Atten. at 700 MHz, dB/100 ft	Max. Op. Voltage, RMS
RG-8A/U	52	0.66	0.405	1.6	3.2	6.5	4000
RG-8/X	50	0.78	0.242	2.5	5.4	11.1	600
RG-213/U	50	0.66	0.405	1.6	3.2	6.5	5000
RG-58/U	53.5	0.66	0.195	3.1	6.8	14.0	1900
RG-58A/U	50	0.66	0.195	3.3	7.3	17.0	1900
RG-58C/U	50	0.66	0.195	3.3	7.3	17.0	1900
RG-11A/U	75	0.66	0.405	1.3	2.9	5.8	5000
RG-59B/U	75	0.66	0.242	2.4	4.9	9.3	2300
RG-62B/U	93	0.84	0.242	2.0	4.2	8.6	750
RG-71/U	93	0.84	0.245	1.9	3.8	7.3	750
RG-141A/U	50	0.695	0.190	2.7	5.6	11.0	1400
RG-178B/U	50	0.695	0.70	10.5	19.0	37.0	1000
RG6A/U	75	0.66	0.332	1.9	4.1	8.1	2700

From Blackwell, G.R., Interconnects, in *The Electronic Packaging Handbook,* Blackwell, G.R., Ed., CRC Press, Boca Raton, FL, 2000, p. **8**-53.



(From Norgard, J., Electromagnetic spectrum, in *The Electronics Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 4.)

Properties of Magnetic Materials and Magnetic Alloys

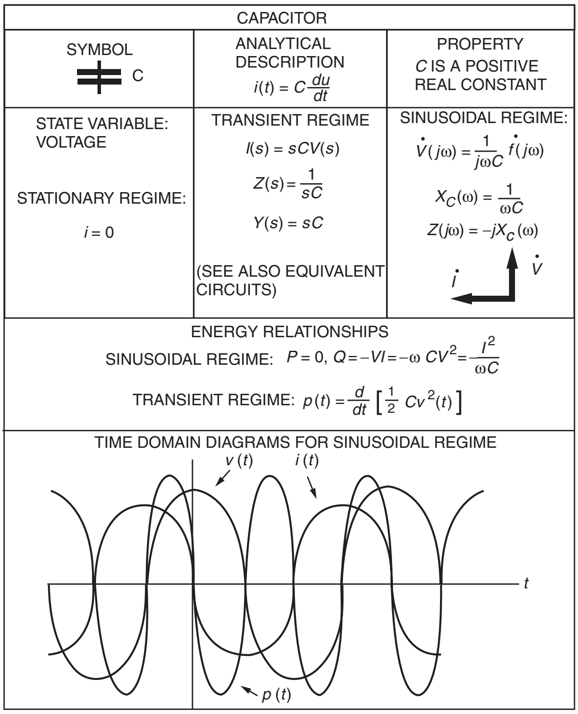
Material (Composition)	Initial Relative Permeability, μ_i/μ_0	Maximum Relative Permeability, μ_{max}/μ_0	Coercive Force *He*, A/m (Oe)	Residual Field B_r, Wb/m^2(G)	Saturation Field B_s, Wb/m^2(G)	Electrical Resistivity $\rho \times 10^{-8}\ \Omega \cdot m$	Uses
Soft							
Commercial iron (0.2 imp.)	250	9000	≈80 (1)	0.77 (7700)	2.15 (21,500)	10	Relays
Purified iron (0.05 imp.)	10,000	200,000	4 (0.05)	—	2.15 (21,500)	10	
Silicon-iron (4 Si)	1500	7000	20 (0.25)	0.5 (5000)	1.95 (19,500)	60	Transformers
Silicon-iron (3 Si)	7500	55,000	8 (0.1)	0.95 (9500)	2 (20,000)	50	Transformers
Silicon-iron (3 Si)	—	116,000	4.8 (0.06)	1.22 (12,200)	2 (20,100)	50	Transformers
Mu metal (5 Cu, 2 Cr, 77 Ni)	20,000	100,000	4 (0.05)	0.23 (2300)	0.65 (6500)	62	Transformers
78 Permalloy (78.5 Ni)	8000	100,000	4 (0.05)	0.6 (6000)	1.08 (10,800)	16	Sensitive relays
Supermalloy (79 Ni, 5 Mo)	100,000	1,000,000	0.16 (0.002)	0.5 (5000)	0.79 (7900)	60	Transformers
Permendur (50 Cs)	800	5000	160 (2)	1.4 (14,000)	2.45 (24,500)	7	Electromagnets
Mn-Zn ferrite	1500	2500	16 (0.2)	—	0.34 (3400)	20×10^6	Core material for coils
Ni-Zn ferrite	2500	5000	8 (0.1)	—	0.32 (3200)	10^{11}	

From Parker, M.R. and Webb, W.E., Magnetic materials for inductive processes, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 151. Originally after Plonus, M.A., 1978, *Applied Electromagnetics*, McGraw-Hill, New York.

Units

Quantity	Symbol	Unit (S.I.)
Magnetic flux density	B	T (or Wb/m^2)
Magnetic field intensity	H	A/m
Magnetic flux	ϕ'	Wb
Magnetic flux linkage	Λ	Wb-turns
Self, mutual inductance	L, M	H
Magnetic permeability	μ	H/m

From Parker, M.R. and Webb, W.E., Magnetic materials for inductive processes, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 154.



Summary of capacitor properties. (From Filanovsky, I.M., Capacitance and capacitors, in *The Electronics Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 168.)

Frequency Response Magnitude Functions for Butterworth LP Prototype Filters

Order n	$\left\|\frac{V_2(\omega)}{V_1(\omega)}\right\|$
2	$\frac{1}{\sqrt{1+\omega^4}}$
3	$\frac{1}{\sqrt{1+\omega^6}}$
4	$\frac{1}{\sqrt{1+\omega^8}}$

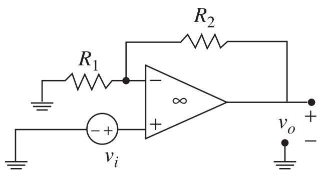
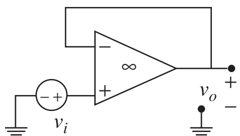
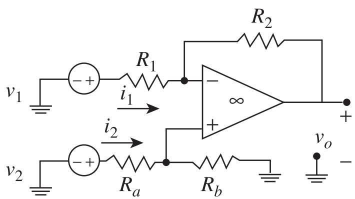
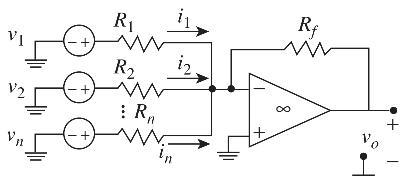
From Harrison, C., Passive filters, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 282.

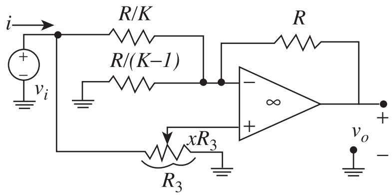
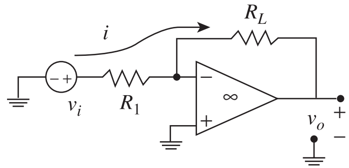
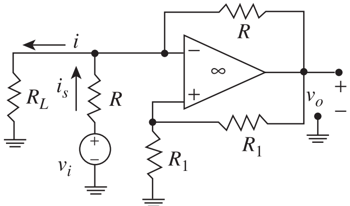
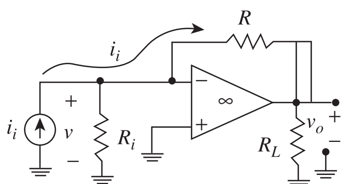
Frequency Response Magnitude Functions for Chebyshev LP Prototype Filters

Order n	Chebyshev Polynomial $T_n(\omega)$	$\left\|\frac{V_2(\omega)}{V_1(\omega)}\right\|$
2	$2\omega^2 - 1$	$\frac{1}{\sqrt{4\varepsilon^2\omega^4 - 4\varepsilon^2\omega^2 + (\varepsilon^2 + 1)}}$
3	$4\omega^3 - 3\omega$	$\frac{1}{\sqrt{16\varepsilon^2\omega^6 - 24\varepsilon^2\omega^4 + 9\varepsilon^2\omega^2 + 1}}$
4	$8\omega^4 - 8\omega^2 + 1$	$\frac{1}{\sqrt{64\varepsilon^2\omega^8 - 128\varepsilon^2\omega^6 + 80\varepsilon^2\omega^4 - 16\varepsilon^2\omega^2 + (\varepsilon^2 + 1)}}$

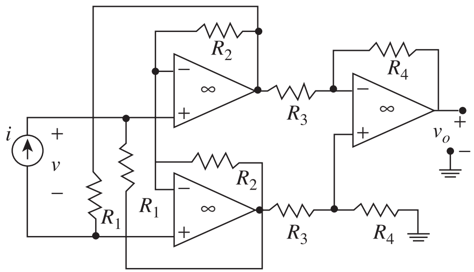
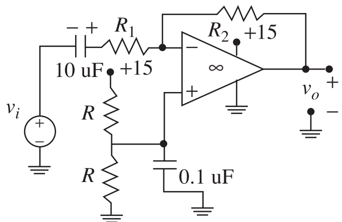
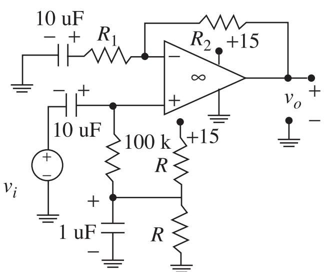
From Harrison, C., Passive filters, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, p. 283.

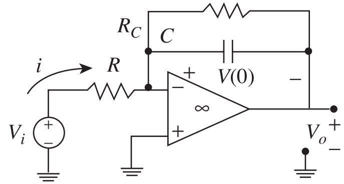
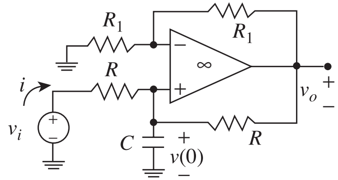
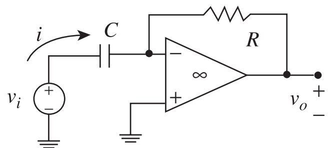
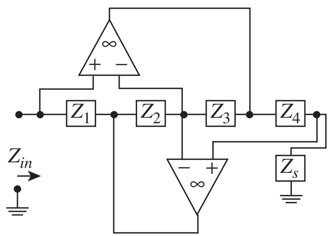
Op–amp Circuits

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
1.	Noninverting amplifier		$\frac{\upsilon_O}{\upsilon_i} = 1 + \frac{R_2}{R_1}$	$R_{in} = \infty$ (ideally)	
2.	Buffer		$\frac{\upsilon_O}{\upsilon_i} = 1$	$R_{in} = \infty$ (ideally)	Special case of circuit 1
3.	Difference amplifier		$\upsilon_O = \frac{R_2}{R_1}(\upsilon_2 - \upsilon_1)$	$i_1 = \frac{\upsilon_1 - \upsilon_2 \frac{R_b}{(R_a + R_b)}}{R_1}$ $i_2 = \frac{\upsilon_2}{R_a + R_b}$	$\frac{R_1}{R_2} = \frac{R_a}{R_b}$
4.	Adder		$\upsilon_O = -\left\{\upsilon_1 \frac{R_f}{R_1} + \upsilon_2 \frac{R_f}{R_2} + \cdots + \upsilon_n \frac{R_f}{R_n}\right\}$	$i_1 = \frac{\upsilon_1}{R_1}$ $i_2 = \frac{\upsilon_2}{R_2}$ ⋮ $i_n = \frac{\upsilon_n}{R_n}$	

5.	Variable gain circuit		$\frac{v_O}{v_i} = (2Kx - K)$ $0 \le x \le 1, \quad K > 1$	$i = \frac{v_i}{R_3} + \frac{Kv_i(1-x)}{R}$	Potentionmeter R_3 adjusts the gain over the range $-K$ to $+K$
6.	Voltage-to-current converter		$i = \frac{v_i}{R_1}$		The current through R_L is independent of R_L
7.	Voltage-to-current converter with grounded load		$i = \frac{v_i}{R}$	$i_s = \frac{v_i}{R}\left(1 - \frac{R_L}{R}\right)$	$v_0 = v_i(2R_L/R)$ The current i is independent of R_L Circuit has wide band-width for $R_L \ll R$
8.	Current-to-voltage converter		$v_0 = -Ri_i$	$v = 0$	The voltage v_0 is independent of R_L and R_i

Op–amp Circuits (continued)

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
9.	Current-to-voltage converter		$\upsilon_O = -2iR_1 \frac{R_4}{R_3}$	$v = 0$	
10.	Inverting amplifier with single supply		$\upsilon_O = 7.5 - \upsilon_i \frac{R_2}{R_1}$		$R = 3.9\ \text{k}\Omega$
11.	Noninverting amplifier with single supply		$\upsilon_O = 7.5 + \upsilon_i \left(1 + \frac{R_2}{R_1}\right)$		$R = 3.9\ \text{k}\Omega$

12.	Integrator		$\upsilon_O = -V(0) - \frac{1}{RC}\int_0^t \upsilon_i(t)dt$ V (0) is the initial voltage across the capacitor, RC is very large.	$i = \frac{\upsilon_i}{R}$	Negative feedback is required at DC. A large value of R_C can be used or a feedback path can be established through an external circuit.
13.	De Boo integrator		$\upsilon_O = 2V(0) + \frac{2}{RC}\int_0^t \upsilon_i(t)dt$	$i = \frac{\upsilon_i}{R} - \frac{\upsilon_O}{2R}$	One end of capacitor is physically grounded.
14.	Differentiator		$\upsilon_O = RC\frac{d\upsilon_i}{dt}$	$i = C\frac{d\upsilon_i}{dt}$	Differentiators are usually avoided in the design of circuits because they accentuate noise.
15.	Generalized impedance converter (GIC)		$Z_{in} = \frac{Z_1Z_3Z_5}{Z_2Z_4}$		

From Aronhime, P., Operational amplifiers, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, pp. 554–556.

Operating Characteristics of Common Battery Types

	NiCd	NiMH	SLA	Li-ion	Li-polymer	Reusable Alkaline
Energy density, Wh/kg	50	75	30	100	175	80 (initial)
Cycle life[a] (typical)	1500	500	200–300	300–500	150	10 (to 65%)
Fast-charge time,[b] h	1 1/2	2–3	8–15	3–6	8–15	3–4
Self-discharge[c]	Moderate[d]	High	Low	Low	Very low	Very low
Cell voltage,[e] (nominal) V	1.25	1.25	2	3.6	2.7	1.5
Load current,[f]	Very high	Moderate	Low	High	Low	Very low
Exercise requirement[g]	/30 days	/90 days	/180 days	N/A	N/A	N/A
Battery cost[h]	Low	Moderate	Very low	Very high	High	Very low
(estimated, ref. only)	(50,000)	(80.00)	(25.00)	(100.00)	(90.00)	(5.00)
Cost per cycle[i] ($)	0.04	0.16	0.10	0.25	0.60	0.50
In commercial use since	1950	1970	1970	1990	(1997)	1990

[a] Cycle life indicates the typical number of charge–discharge cycles before the capacity decreases from the nominal 100% to 80% (65% for the reusable alkaline).

[b] Fast-charge time is the time required to fully charge an empty battery.

[c] Self-discharge indicates the self-discharge rate when the battery is not in use.

[d] Moderate refers to 1–2% capacity-loss per day.

[e] Cell voltage multiplied by the number of cells provides the battery terminal voltage.

[f] Load current is the maximum recommended current the battery can provide. High refers to a discharge rate of 1C; very high is a current higher than 1 *C*. C rate is a unit by which charge and discharge times are scaled. If discharged at 1, a 1000 mAh battery provides a current of 1000 mA; if discharged at 0.5C, the current is 500 mA.

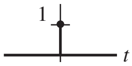
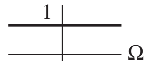
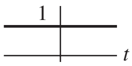
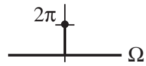
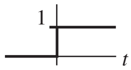
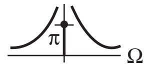
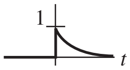
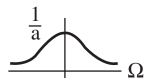
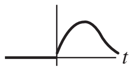
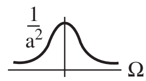
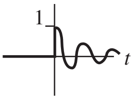
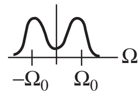
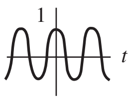
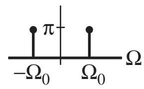
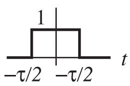
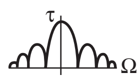
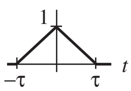
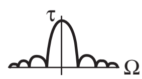
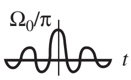
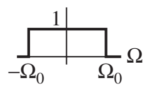
[g] Exercise requirement indicates the frequency the battery needs exercising to achieve maximum service life.

[h] Battery cost is the estimated commercial price of a commonly available battery.

[i] Cost-per-cycle indicates the operating cost derived by taking the average price of a commercial battery and dividing it by the cycle count.

From Buchmann, I., Batteries, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, pp. 1056.

Example Fourier Transform Pairs

$x(t)$	$x(t)$	$X(\Omega)$	$\lvert X(\Omega)\rvert$
	$\delta(t)$	1	
	1	$2\pi\delta(\Omega)$	
	$u(t)$	$\pi\delta(\Omega)+\dfrac{1}{j\Omega}$	
	$e^{-at}u(t),\ a>0$	$\dfrac{1}{a+j\Omega}$	
	$te^{-at}u(t),\ a>0$	$\dfrac{1}{(a+j\Omega)^2}$	
	$e^{-at}\cos(\Omega_0 t)u(t),\ a>0$	$\dfrac{a+j\Omega}{(a+j\Omega)^2+\Omega_0^2}$	
	$\cos(\Omega_0 t)$	$\pi[\delta(\Omega-\Omega_0)+\delta(\Omega+\Omega_0)]$	
	$1, \lvert t\rvert<\tau/2$ $0, \lvert t\rvert>\tau/2$	$\dfrac{\sin(\Omega\tau/2)}{\Omega/2}$	
	$1-\lvert t\rvert/\tau,\ \lvert t\rvert<\tau$ $0, \lvert t\rvert>\tau$	$\dfrac{1}{\tau}\dfrac{\sin^2(\Omega\tau/2)}{(\Omega/2)^2}$	
	$\dfrac{\sin(\Omega_0 t/2)}{\pi t}$	$1, \lvert\Omega\rvert<\Omega_0$ $0, \lvert\Omega\rvert>\Omega_0$	

From Hamann, J.C. and Pierre, J.W., Fourier waveform analysis, in *The Electronics Handbook*, Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 1997, pp. 2119.

Advantages and Disadvantages of Satellites

Advantages	Disadvantages
Wide-area coverage	Propagation delay
Easy access to remote sites	Dependency on a remote facility
Costs independent of distance	Less control over transmission
Low error rates	Attenuation due to atmospheric particles (e.g., rain) severe at high frequencies
Adaptable to changing network patterns	Continual time-of-use charges
No right-of-way necessary; earth stations located at premises	Reduced transmission during solar equinox

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-2. Originally from D.J. Marihart, *IEEE Transactions on Power Delivery,* 16, 181–188, 2001.

Satellite Frequency Allocations

Frequency Band	Range (GHz)
L	1–2
S	2–4
C	4–8
X	8–12
Ku	12–18
K	18–27
Ka	27–40

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-5.

Typical Uplink and Downlink Satellite Frequencies (GHz)

Uplink Frequencies	Downlink Frequencies
5.925–6.425	3.700–4.200
7.900–8.400	7.250–7.750
14.00–14.50	11.70–12.20
27.50–30.00	17.70–20.20

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-5.

Frequency Allocations for FSS (Below ~30 GHz)

Downlinks (in GHz)	Uplinks (in GHz)
3.4–4.2 and 4.5–4.8	5.725–7.075
7.25–7.75	7.9–8.4
10.7–11.7	
11.7–12.2 (Region 2 only)	12.75 13.25 and 14.0–14.5
12.5–12.75 (Region 1 only)	
17.7–21.2	27.5–31.0

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-13.

Characteristics of Satellite PCS Systems

Parameter	Iridium	Globalstar	ICO
Company	Motorola	Loral/Qualcomm	ICO-Global
No. of satellites	66	48	10
No. of orbit planes	6	8	2
Altitude (km)	780	1414	10,355
Weight (lb)	1100	704	6050
Bandwidth (MHz)	5.15	11.35	30
Frequency up/down (GHz)	30/20	5.1/6.9	14/12
Spot beams/satellite	48	16	163
Carrier bit rate (k/sec)	50	2.4	36
Multiple access	TDMA/FDMA	CDMA/FDMA	TDMA/FDMA
Cost to build ($billion)	4.7	2.5	4.6
Service start date	1998	1999	2003

From Sadiku, M.N.O., Satellite communications, in *The Handbook of Ad Hoc Wireless Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. **8**-20.

Table of Laplace Operations

	$F(s)$	$fs(t)$
1.	$\int_0^{\infty} e^{-st} f(t)dt$	$f(t)$
2.	$AF(s) + BG(s)$	$Af(t) + Bg(t)$
3.	$sF(s) - f(+0)$	$f'(t)$
4.	$s^n F(s) - s^{n-1} f(+0) - s^{n-2} f^{(1t)}(+0) - \cdots - f^{(n-l)}(+0)$	$f^{(n)}(t)$
5.	$\frac{1}{s}F(s)$	$\int_0^t f(\tau)d\tau$
6.	$\frac{1}{s^2}F(s)$	$\int_0^t \int_0^{\tau} f(\lambda)d\lambda\, d\tau$
7.	$F_1(s)F_2(s)$	$\int_0^t f_1(t-\tau)f_2(\tau)d\tau = f_1 * f_2$
8.	$-F'(s)$	$tf(t)$
9.	$(-1)^n F^{(n)}(s)$	$t^n f(t)$
10.	$\int_s^{\infty} F(x)dx$	$\frac{1}{t}f(t)$
11.	$F(s-a)$	$e^{at}f(t)$
12.	$e^{-bs}F(s)$	$f(t-b)$, where $f(t) = 0;\ t < 0$
13.	$F(cs)$	$\frac{1}{c}f\left(\frac{t}{c}\right)$
14.	$F(cs-b)$	$\frac{1}{c}e^{(bt)/c}f\left(\frac{t}{c}\right)$
15.	$\frac{\int_0^a e^{-st}f(t)dt}{1-e^{-as}}$	$f(t+a) = f(t)$ periodic signal
16.	$\frac{\int_0^a e^{-st}f(t)dt}{1+e^{-as}}$	$f(t+a) = -f(t)$
17.	$\frac{F(s)}{1-e^{-as}}$	$f_1(t)$, the half-wave rectification of $f(t)$ in No. 16.

Table of Laplace Operations (continued)

	$F(s)$	$fs(t)$
18.	$F(s)\coth\frac{as}{2}$	$f_2(f)$, the full-wave rectification of $f(t)$ in No. 16.
19.	$\frac{p(s)}{q(s)}, q(s)=(s-a_1)(s-a_2)\cdots(s-a_m)$	$\sum_{1}^{m}\frac{p(a_n)}{q'(a_n)}e^{a_n t}$
20.	$\frac{p(s)}{q(s)}=\frac{\phi(s)}{(s-a)^r}$	$e^{at}\sum_{n=1}^{r}\frac{\phi^{(r-n)}(a)}{(r-n)!}\frac{t^{n-1}}{(n-1)!}+\cdots$

From Poularikas, A., Laplace transforms, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, p. **2**-6.

Table of Laplace Transforms

	$F(s)$	$f(t)$
1.	s^n	$\delta^{(n)}(t)$ n^{th} derivative of the delta function
2.	s	$\frac{d\delta(t)}{dt}$
3.	1	$\delta(t)$
4.	$\frac{1}{s}$	1
5.	$\frac{1}{s^2}$	t
6.	$\frac{1}{s^n}(n=1,2,\cdots)$	$\frac{t^{n-1}}{(n-1)!}$
7.	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{\pi t}}$
8.	$s^{-3/2}$	$2\sqrt{\frac{t}{\pi}}$
9.	$s^{-[n+(1/2)]}$ $(n = 1,2,\cdots)$	$\frac{2^n t^{n-(1/2)}}{1\cdot 3\cdot 5\cdots(2n-1)\sqrt{\pi}}$
10.	$\frac{\Gamma(k)}{s^k}(k\geq 0)$	t^{k-1}
11.	$\frac{1}{s-a}$	e^{at}
12.	$\frac{1}{(s-a)^2}$	te^{at}
13.	$\frac{1}{(s-a)^n}(n=1,2,\cdots)$	$\frac{1}{(n-1)!}t^{n-1}e^{at}$
14.	$\frac{\Gamma(k)}{(s-a)^k}(k\geq 0)$	$t^{k-1}\ e^{at}$
15.	$\frac{1}{(s-a)(s-b)}$	$\frac{1}{(a-b)}(e^{at}-e^{bt})$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
16.	$\frac{s}{(s-a)(s-b)}$	$\frac{1}{(a-b)}\left(ae^{at}-be^{bt}\right)$
17.	$\frac{1}{(s-a)(s-b)(s-c)}$	$-\frac{(b-c)e^{at}+(c-a)e^{bt}+(a-b)e^{ct}}{(a-b)(b-c)(c-a)}$
18.	$\frac{1}{(s+a)}$	e^{-at} valid for complex a
19.	$\frac{1}{s(s+a)}$	$\frac{1}{a}\left(1-e^{-at}\right)$
20.	$\frac{1}{s^2(s+a)}$	$\frac{1}{a^2}\left(e^{-at}+at-1\right)$
21.	$\frac{1}{s^3(s+a)}$	$\frac{1}{a^2}\left[\frac{1}{a}-t+\frac{at^2}{2}-\frac{1}{a}e^{-at}\right]$
22.	$\frac{1}{(s+a)(s+b)}$	$\frac{1}{(b-a)}\left(e^{-at}-e^{-bt}\right)$
23.	$\frac{1}{s(s+a)(s+b)}$	$\frac{1}{ab}\left[1+\frac{1}{(a-b)}\left(be^{-at}-ae^{-bt}\right)\right]$
24.	$\frac{1}{s^2(s+a)(s+b)}$	$\frac{1}{(ab)^2}\left[\frac{1}{(a-b)}\left(a^2e^{-bt}-b^2e^{-at}\right)+abt-a-b\right]$
25.	$\frac{1}{s^3(s+a)(s+b)}$	$\frac{1}{(ab)}\left[\frac{a^3-b^3}{(ab)^2(a-b)}+\frac{1}{2}t^2-\frac{(a+b)}{ab}t+\frac{1}{(a-b)}\left(\frac{b}{a^2}e^{-at}-\frac{a}{b^2}e^{-bt}\right)\right]$
26.	$\frac{1}{(s+a)(s+b)(s+c)}$	$\frac{1}{(b-a)(c-a)}e^{-at}+\frac{1}{(a-b)(c-b)}e^{-bt}+\frac{1}{(a-c)(b-c)}e^{-ct}$
27.	$\frac{1}{s(s+a)(s+b)(s+c)}$	$\frac{1}{abc}-\frac{1}{a(b-a)(c-a)}e^{-at}-\frac{1}{b(a-b)(c-b)}e^{-bt}-\frac{1}{c(a-c)(b-c)}e^{-ct}$
28.	$\frac{1}{s^2(s+a)(s+b)(s+c)}$	$\frac{ab(ct-1)-ac-bc}{(abc)^2}+\frac{1}{a^2(b-a)(c-a)}e^{-at}+\frac{1}{b^2(a-b)(c-b)}e^{-bt}+\frac{1}{c^2(a-c)(b-c)}e^{-ct}$
29.	$\frac{1}{s^3(s+a)(s+b)(s+c)}$	$\frac{1}{(abc)^3}\left[(ab+ac+bc)^2-abc(a+b+c)\right]-\frac{ab+ac+bc}{(abc)^2}t+\frac{1}{2abc}t^2-\frac{1}{a^3(c-a)(c-a)}e^{-at}-\frac{1}{b^3(a-b)(c-b)}e^{-bt}-\frac{1}{c^3(a-c)(b-c)}\varepsilon^{-ct}$
30.	$\frac{1}{s^2+a^2}$	$\frac{1}{a}\sin at$
31.	$\frac{s}{s^2+a^2}$	$\cos at$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
32.	$\frac{1}{s^2-a^2}$	$\frac{1}{a}\sinh at$
33.	$\frac{s}{s^2-a^2}$	$\cosh at$
34.	$\frac{1}{s(s^2+a^2)}$	$\frac{1}{a^2}(1-\cos at)$
35.	$\frac{1}{s^2(s^2+a^2)}$	$\frac{1}{a^3}(at-\sin at)$
36.	$\frac{1}{(s^2+a^2)^2}$	$\frac{1}{2a^3}(\sin at - at\cos at)$
37.	$\frac{1}{(s^2+a^2)^2}$	$\frac{1}{2a}\sin at$
38.	$\frac{s^2}{(s^2+a^2)^2}$	$\frac{1}{2a}(\sin at + at\cos at)$
39.	$\frac{s^2-a^2}{(s^2+a^2)^2}$	$t\cos at$
40.	$\frac{s}{(s^2+a^2)(s^2+b^2)}\left(a^2\neq b^2\right)$	$\frac{\cos at-\cos bt}{b^2-a^2}$
41.	$\frac{1}{(s-a)^2+b^2}$	$\frac{1}{b}e^{at}\sin bt$
42.	$\frac{s-a}{(s-a)^2+b^2}$	$e^{at}\cos bt$
43.	$\frac{1}{\left[(s+s)^2+b^2\right]^n}$	$\frac{-e^{-at}}{4^{n-1}b^{2n}}\sum_{r=1}^{n}\binom{2n-r-1}{n-1}(-2t)^{r-1}\frac{d^r}{dt^r}\left[\cos(bt)\right]$
44.	$\frac{s}{\left[(s+a)^2b^2\right]^n}$	$\left\{\begin{array}{l}\frac{e^{-at}}{4^{n-1}b^{2n}}\sum_{r=1}^{n}\binom{2n-r-1}{n-1}(-2t)^{r-1}\frac{d^r}{dt^r}\left[a\cos(bt)+b\sin(bt)\right]\\ -2b\sum_{r=1}^{n-1}r\binom{2n-r-2}{n-1}(-2t)^{r-1}\frac{d^r}{dt^r}\left[\sin(bt)\right]\end{array}\right\}$
45.	$\frac{3a^2}{s^3+a^3}$	$e^{-at}-e^{(at)/2}\left(\cos\frac{at\sqrt{3}}{2}-\sqrt{3}\sin\frac{at\sqrt{3}}{2}\right)$
46.	$\frac{4a^3}{s^4+4a^4}$	$\sin at\cosh at - \cos at\sinh at$
47.	$\frac{s}{s^4+4a^4}$	$\frac{1}{2a^2}(\sin at\cdot\sinh at)$
48.	$\frac{1}{s^4-a^4}$	$\frac{1}{2a^3}(\sinh at-\sin at)$
49.	$\frac{s}{s^4-a^4}$	$\frac{1}{2a^2}(\cosh at-\cos at)$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
50.	$\frac{8a^3s^2}{(s^2+a^2)^3}$	$(1 + a^2t^2) \sin at - \cos at$
51.	$\frac{1}{s}\left(\frac{s-1}{s}\right)^n$	$L_n(t) = \frac{e^t}{n!}\frac{d^n}{dt^n}\left(t^n e^{-t}\right)$ [$L_n(t)$ is the Laguerre polynomial of degree n]
52.	$\frac{1}{(s+a)^n}$	$\frac{t^{(n-1)}e^{-at}}{(n-1)!}$ where n is a positive integer
53.	$\frac{1}{s(s+a)^2}$	$\frac{1}{a^2}\left[1-e^{-at}-ate^{-at}\right]$
54.	$\frac{1}{s^2(s+a)^2}$	$\frac{1}{a^3}\left[at-2+ate^{-at}+2e^{-at}\right]$
55.	$\frac{1}{s(s+a)^3}$	$\frac{1}{a^3}\left[1-\left(\frac{1}{2}a^2t^2+at+1\right)e^{-at}\right]$
56.	$\frac{1}{(s+a)(s+b)^2}$	$\frac{1}{(a-b)^2}\left\{e^{-at}+\left[(a-b)t-1\right]e^{-bt}\right\}$
57.	$\frac{1}{s(s+a)(s+b)^2}$	$\frac{1}{ab^2}-\frac{1}{a(a-b)^2}e^{-at}-\left[\frac{1}{b(a-b)}t+\frac{a-2b}{b^2(a-b)^2}\right]e^{-bt}$
58.	$\frac{1}{s^2(s+a)(s+b)^2}$	$\frac{1}{a^2(a-b)^2}e^{-at}+\frac{1}{ab^2}\left(t-\frac{1}{a}-\frac{2}{b}\right)+\left[\frac{1}{b^2(a-b)}t+\frac{2(a-b)-b}{b^3(a-b)^2}\right]e^{-bt}$
59.	$\frac{1}{(s+a)(s+b)(s+c)^2}$	$\left\{\left[\frac{1}{(c-b)(c-a)}i+\frac{2c-a-b}{(c-a)^2(c-b)^2}\right]e^{-ct} + \frac{1}{(b-a)(c-a)^2}e^{-at}+\frac{1}{(a-b)(c-b)^2}e^{-bt}\right.$
60.	$\frac{1}{(s+a)(s^2+\omega^2)}$	$\frac{1}{a^2+\omega^2}e^{-at}+\frac{1}{\omega\sqrt{a^2+\omega^2}}\sin(\omega t-\phi);\ \phi=\tan^{-1}\left(\frac{\omega}{a}\right)$
61.	$\frac{1}{s(s+a)(s^2+\omega^2)}$	$\frac{1}{a\omega^2}-\frac{1}{a^2+\omega^2}\left(\frac{1}{\omega}\sin\omega t+\frac{a}{\omega^2}\cos\omega t+\frac{1}{a}e^{-at}\right)$
62.	$\frac{1}{s^2(s+a)(s^2+\omega^2)}$	$\left\{\frac{1}{a\omega^2}t-\frac{1}{a^2\omega^2}+\frac{1}{a^2(a^2+\omega^2)}e^{-at} + \frac{1}{\omega^3\sqrt{a^2+\omega^2}}\cos(\omega t+\phi);\ \phi=\tan^{-1}\left(\frac{a}{\omega}\right)\right.$
63.	$\frac{1}{\left[(s+a)^2+\omega^2\right]^2}$	$\frac{1}{2\omega^3}e^{-at}\left[\sin\omega t-\omega t\cos\omega t\right]$
64.	$\frac{1}{s^2-a^2}$	$\frac{1}{a}\sinh at$
65.	$\frac{1}{s^2(s^2-a^2)}$	$\frac{1}{a^3}\sinh at-\frac{1}{a^2}t$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
66.	$\frac{1}{s^3(s^2-a^2)}$	$\frac{1}{a^4}(\cosh at - 1) - \frac{1}{2a^2}t^2$
67.	$\frac{1}{s^3+a^3}$	$\frac{1}{3a^2}\left[e^{-at} - e^{\frac{a}{2}t}\left(\cos\frac{\sqrt{3}}{2}at - \sqrt{3}\sin\frac{\sqrt{3}}{2}at\right)\right]$
68.	$\frac{1}{s^4+4a^4}$	$\frac{1}{4a^3}(\sin at \cosh at - \cos at \sinh at)$
69.	$\frac{1}{s^4-a^4}$	$\frac{1}{2a^3}(\sinh at - \sin at)$
70.	$\frac{1}{\left[(s+a)^2-\omega^2\right]}$	$\frac{1}{\omega}e^{-at}\sinh \omega t$
71.	$\frac{s+a}{s\left[(s+b)^2+\omega^2\right]}$	$\begin{cases} \frac{a}{b^2+\omega^2} - \frac{1}{\omega} + \sqrt{\frac{(a-b)^2+\omega^2}{b^2+\omega^2}}e^{-bt}\sin(\omega t+\phi); \\ \phi = \tan^{-1}\left(\frac{\omega}{b}\right) + \tan^{-1}\left(\frac{\omega}{a-b}\right) \end{cases}$
72.	$\frac{s+a}{s^2\left[(s+b)^2+\omega^2\right]}$	$\begin{cases} \frac{1}{b^2+\omega^2}[1+at] - \frac{2ab}{(b^2+\omega^2)^2} + \frac{\sqrt{(a-b)^2+\omega^2}}{\omega(b^2+\omega^2)}e^{-bt}\sin(\omega t+\phi) \\ \phi = \tan^{-1}\left(\frac{\omega}{a-b}\right) + 2\tan^{-1}\left(\frac{\omega}{b}\right) \end{cases}$
73.	$\frac{s+a}{(s+c)\left[(s+b)^2+\omega^2\right]}$	$\begin{cases} \frac{a-c}{(c-b)^2+\omega^2}e^{-ct} + \frac{1}{\omega}\sqrt{\frac{(a-b)^2+\omega^2}{(c-b)^2+\omega^2}}e^{-bt}\sin(\omega t+\phi) \\ \phi = \tan^{-1}\left(\frac{\omega}{a-b}\right) - \tan^{-1}\left(\frac{\omega}{c-b}\right) \end{cases}$
74.	$\frac{s+a}{s(s+c)\left[(s+b)^2+\omega^2\right]}$	$\begin{cases} \frac{a}{c(b^2+\omega^2)} + \frac{(c-a)}{c\left[(b-c)^2+\omega^2\right]}e^{-ct} \\ -\frac{1}{\omega\sqrt{b^2+\omega^2}}\sqrt{\frac{(a-b)^2+\omega^2}{(b-c)^2+\omega^2}}e^{-bt}\sin(\omega t+\phi) \\ \phi = \tan^{-1}\left(\frac{\omega}{b}\right) + \tan^{-1}\left(\frac{\omega}{a-b}\right) - \tan^{-1}\left(\frac{\omega}{c-b}\right) \end{cases}$
75.	$\frac{s+a}{s^2(s+b)^3}$	$\frac{a}{b^3} + \frac{b-3a}{b^4} + \left[\frac{3a-b}{b^4} + \frac{a-b}{2b^2}t^2 + \frac{2a-b}{b^3}t\right]e^{-bt}$
76.	$\frac{s+a}{(s+c)(s+b)^3}$	$\frac{a-c}{(b-c)^3}e^{-ct} + \left[\frac{a-b}{2(c-b)}t^2 + \frac{c-a}{(c-b)^2}t + \frac{a-c}{(c-b)^3}\right]e^{-bt}$
77.	$\frac{s^2}{(s+a)(s+b)(s+c)}$	$\frac{a^2}{(b-a)(c-a)}e^{-at} + \frac{b^2}{(a-b)(c-b)}e^{-bt} + \frac{c^2}{(a-c)(b-c)}e^{-ct}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
78.	$\dfrac{s^2}{(s+a)(s+b)^2}$	$\dfrac{a^2}{(b-a)^2}e^{-at}+\left[\dfrac{b^2}{(a-b)}t+\dfrac{b^2-2ab}{(a-b)^2}\right]e^{-bt}$
79.	$\dfrac{s^2}{(s+a)^3}$	$\left[2-2at+\dfrac{a^2}{2}t^2\right]e^{-at}$
80.	$\dfrac{s^2}{(s+a)(s^2+\omega^2)}$	$\dfrac{a^2}{(a^2+\omega^2)}e^{-at}-\dfrac{\omega}{\sqrt{a^2+\omega^2}}\sin(\omega t+\phi);\ \phi\tan^{-1}\left(\dfrac{\omega}{a}\right)$
81.	$\dfrac{s^2}{(s+a)^2(s^2+\omega^2)}$	$\left[\dfrac{a^2}{(a^2+\omega^2)}t-\dfrac{2a\omega^2}{(a^2+\omega^2)^2}\right]e^{-at}-\dfrac{\omega}{(a^2+\omega^2)}\sin(\omega t+\phi);$ $\phi=-2\tan^{-1}\left(\dfrac{\omega}{a}\right)$
82.	$\dfrac{s^2}{(s+a)(s+b)(s^2+\omega^2)}$	$\dfrac{a^2}{(b-a)(a^2+\omega^2)}e^{-at}+\dfrac{b^2}{(a-b)(b^2+\omega^2)}e^{-bt}$ $-\dfrac{\omega}{\sqrt{(a^2+\omega^2)(b^2+\omega^2)}}\sin(\omega t+\phi);\ \phi=-\left[\tan^{-1}\left(\dfrac{\omega}{a}\right)+\tan^{-1}\left(\dfrac{\omega}{b}\right)\right]$
83.	$\dfrac{s^2}{(s^2+a^2)(s^3+\omega^2)}$	$-\dfrac{a}{(\omega^2-a^2)}\sin(at)-\dfrac{\omega}{(a^2-\omega^2)}\sin(\omega t)$
84.	$\dfrac{s^2}{(s^2+\omega^2)^2}$	$\dfrac{1}{2\omega}(\sin\omega t+\omega t\cos\omega t)$
85.	$\dfrac{s^2}{(s+a)\left[(s+b)^2+\omega^2\right]}$	$\dfrac{a^2}{(a-b)^2+\omega^2}e^{-at}+\dfrac{1}{\omega}\sqrt{\dfrac{(b^2-\omega^2)^2+4b^2\omega^2}{(a-b)^2+\omega^2}}e^{-bt}\sin(\omega t+\phi)$ $\phi=\tan^{-1}\left(\dfrac{-sb\omega}{b^2-\omega^2}\right)-\tan^{-1}\left(\dfrac{\omega}{a-b}\right)$
86.	$\dfrac{s^2}{(s+a)^2\left[(s+b)^2+\omega^2\right]}$	$\dfrac{a^2}{(a-b)^2+\omega^2}te^{-at}-2\left[\dfrac{a\left[(b-a)^2+\omega^2\right]+a^2(b-a)}{\left[(b-a)^2+\omega^2\right]^2}\right]e^{-at}$ $+\dfrac{\sqrt{(b^2-\omega^2)^2+4b^2\omega^2}}{\omega\left[(a-b)^2+\omega^2\right]}e^{-bt}\sin(\omega t+\phi)$ $\phi=\tan^{-1}\left(\dfrac{-2b\omega}{b^2-\omega^2}\right)-2\tan^{-1}\left(\dfrac{\omega}{a-b}\right)$
87.	$\dfrac{s^2+a}{s^2(s+b)}$	$\dfrac{b^2+a}{b^2}e^{-bt}+\dfrac{a}{b}t-\dfrac{a}{b^2}$
88.	$\dfrac{s^2+a}{s^3(s+b)}$	$\dfrac{a}{2b}t^2-\dfrac{a}{b^2}t+\dfrac{1}{b^3}\left[b^2+a-(a+b^2)e^{-bt}\right]$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
89.	$\frac{s^2+a}{s(s+b)(s+c)}$	$\frac{a}{bc}+\frac{(b^2+a)}{b(b-c)}e^{-bt}-\frac{(c^2+a)}{c(b-c)}e^{-ct}$
90.	$\frac{s^2+a}{s^2(s+b)(s+c)}$	$\frac{b^2-a}{b^2(c-b)}e^{-bt}+\frac{c^2+a}{c^2(b-c)}e^{-ct}+\frac{a}{bc}t-\frac{a(b+c)}{b^2c^2}$
91.	$\frac{s^2+a}{(s+b)(s+c)(s+d)}$	$\frac{b^2+a}{(c-b)(d-b)}e^{-bt}+\frac{c^2+a}{(b-c)(d-c)}e^{-ct}+\frac{d^2+a}{(b-d)(c-d)}e^{-dt}$
92.	$\frac{s^2+a}{s(s+b)(s+c)(s+d)}$	$\frac{a}{bcd}+\frac{b^2+a}{b(b-c)(d-b)}e^{-bt}+\frac{c^2a}{c(b-c)(c-d)}e^{-ct}\frac{d^2+a}{d(b-d)(d-c)}e^{-dt}$
93.	$\frac{s^2+a}{s^2(s+b)(s+c)(s+d)}$	$\left\{\begin{array}{l}\frac{a}{bcd}t-\frac{a}{b^2c^2d^2}(bc+cd+db)+\frac{b^2+a}{b^2(b-c)(b-d)}e^{-bt}\\ +\frac{c^2+a}{c^2(c-b)(c-d)}e^{-ct}+\frac{d^2+a}{d^2(d-b)(d-c)}e^{-dt}\end{array}\right.$
94.	$\frac{s^2+a}{(s^2+\omega^2)^2}$	$\frac{1}{2\omega^3}(a+\omega^2)\sin\omega t-\frac{1}{2\omega^2}(a-\omega^2)t\cos\omega t$
95.	$\frac{s^2-\omega^2}{(s^2+\omega^2)^2}$	$t\cos\omega t$
96.	$\frac{s^2+a}{s(s^2+\omega^2)^2}$	$\frac{a}{\omega^4}-\frac{(a-\omega^2)}{2\omega^3}t\sin\omega t-\frac{a}{\omega^4}\cos\omega t$
97.	$\frac{s(s+a)}{(s+b)(s+c)^2}$	$\frac{b^2-ab}{(c-b)^2}e^{-bt}+\left[\frac{c^2-ac}{b-c}t+\frac{c^2-2bc+ab}{(b-c)^2}\right]e^{-ct}$
98.	$\frac{s(s+a)}{(s+b)(s+c)(s+d)^2}$	$\left\{\begin{array}{l}\frac{b^2-ab}{(c-b)(d-b)^2}e^{-bt}+\frac{c^2-ac}{(b-c)(d-c)^2}e^{-ct}+\frac{d^2-ad}{(b-d)(c-d)}te^{-dt}\\ +\frac{a(bc-d^2)+d(db+dc-2bc)}{(b-d)^2(c-d)^2}e^{-dt}\end{array}\right.$
99.	$\frac{s^2+a_1s+a_o}{s^2(s+b)}$	$\frac{b^2-a_1b+a_o}{b^2}e^{-bt}+\frac{a_o}{b}t+\frac{a_1b-a_o}{b^2}$
100.	$\frac{s^2+a_1s+a_o}{s^3(s+b)}$	$\frac{a_1b-b^2-a_o}{b^3}e^{-bt}+\frac{a_o}{2b}t^2+\frac{a_1b-a_o}{b^2}t+\frac{b^2-a_1b+a_o}{b^3}$
101.	$\frac{s^2+a_1s+a_o}{s(s+b)(s+c)}$	$\frac{a_o}{bc}+\frac{b^2-a_1b+a_o}{b(b-c)}e^{-bt}+\frac{c^2-a_1c+a_o}{c(c-b)}e^{-ct}$
102.	$\frac{s^2+a_1s+a_o}{s^2(s+b)(s+c)}$	$\frac{a_o}{bc}t+\frac{a_1bc-a_o(b+c)}{b^2c^2}+\frac{b^2-a_1b+a_o}{b^2(c-b)}e^{-bt}+\frac{c^2-a_1c+a_o}{c^2(b-c)}e^{-ct}$
103.	$\frac{s^2+a_1s+a_o}{(s+b)(s+c)(s+d)}$	$\frac{b^2-a_1b+a_o}{(c-b)(d-b)}e^{-bt}+\frac{c^2-a_1c+a_o}{(b-c)(d-c)}e^{-ct}+\frac{d^2-a_1d+a_o}{(b-d)(c-d)}e^{-dt}$
104.	$\frac{s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)}$	$\frac{a_o}{bcd}-\frac{b^2-a_1b+a_o}{b(c-b)(d-b)}e^{-bt}-\frac{c^2-a_1c+a_o}{c(b-c)(d-c)}e^{-ct}-\frac{d^2-a_1d+a_o}{d(b-d)(c-d)}e^{-dt}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
105.	$\frac{s^2+a_1s+a_o}{s(s+b)^2}$	$\frac{a_o}{b^2}-\frac{b^2-a_1b+a_o}{b}te^{-bt}+\frac{b^1-a_o}{b^2}e^{-bt}$
106.	$\frac{s^2+a_1s+a_o}{s^2(s+b)^2}$	$\frac{a_o}{b^2}t+\frac{a_1b-2a_o}{b^3}+\frac{b^2-a_1b+a_o}{b^2}t\varepsilon^{-bt}+\frac{2a_o-a_1b}{b^3}e^{-bt}$
107.	$\frac{s^2+a_1s+a_o}{(s+b)(s+c)^2}$	$\frac{b^2-a_1b+a_o}{(c-b)^2}e^{-bt}+\frac{c^2-a_1c+a_o}{(b-c)}te^{-ct}+\frac{c^2-2bc+a_1b-a_o}{(b-c)^2}e^{-ct}$
108.	$\frac{s^2}{(s+b)(s+c)(s+d)^2}$	$\left\{\begin{array}{l}\frac{b^3}{(b-c)(d-b)^2}e^{-bt}+\frac{c^3}{(c-b)(d-c)^2}e^{-ct}+\frac{d^3}{(d-b)(c-d)}te^{-dt}\\ +\frac{d^2\left[d^2-2d(b+c)+3bc\right]}{(b-d)^2(c-d)^2}e^{-dt}\end{array}\right.$
109.	$\frac{s^3}{(s+b)(s+c)(s+d)(s+f)^2}$	$\left\{\begin{array}{l}\frac{b^3}{(b-c)(d-b)(f-b)^2}e^{-bt}+\frac{c^3}{(c-b)(d-c)(f-c)^2}e^{-ct}\\ +\frac{d^2}{(d-b)(c-d)(f-d)^2}e^{-dt}+\frac{f^3}{(f-b)(c-f)(d-f)}te^{-ft}\\ +\left[\frac{3f^2}{(b-f)(c-f)(d-f)}\right.\\ \left.+\frac{f^3\left[(b-f)(c-f)+(b-f)(d-f)+(c-f)(d-f)\right]}{(b-f)^2(c-f)^2(d-f)^2}\right]\varepsilon^{-dt}\end{array}\right.$
110.	$\frac{s^3}{(s+b)^2(s+c)^2}$	$-\frac{b^3}{(c-b)^2}te^{-bt}+\frac{b^2(3c-b)}{(c-b)^3}e^{-bt}-\frac{c^3}{(b-c)^2}te^{-ct}+\frac{c^2(3b-c)}{(b-c)^3}e^{-ct}$
111.	$\frac{s^3}{(s+d)(s+b)^2(s+c)^2}$	$\left\{\begin{array}{l}-\frac{d^3}{(b-d)^2(c-d)^2}e^{-dt}+\frac{b^3}{(c-b)^2(b-d)}te^{-bt}\\ +\left[\frac{3b^2}{(c-b)^2(d-b)}+\frac{b^3(c+2d-3b)}{(c-b)^3(d-b)^2}\right]e^{-bt}+\frac{c^3}{(b-c)^2(c-d)}te^{-ct}\\ +\left[\frac{3c^2}{(b-c)^2(d-c)}+\frac{c^3(b+2d-3c)}{(b-c)^3(d-c)^2}\right]e^{-ct}\end{array}\right.$
112.	$\frac{s^3}{(s+b)(s+c)(s^2+\omega^2)}$	$\left\{\begin{array}{l}\frac{b^3}{(b-c)(b^2+\omega^2)}e^{-bt}+\frac{c^3}{(c-b)(c^2+\omega^2)}e^{-ct}\\ -\frac{\omega^2}{\sqrt{(b^2+\omega^2)(c^2+\omega^2)}}\sin(\omega t+\phi)\\ \phi=\tan^{-1}\left(\frac{c}{\omega}\right)-\tan^{-1}\left(\frac{\omega}{b}\right)\end{array}\right.$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
113.	$\dfrac{s^3}{(s+b)(s+c)(s+d)(s^2+\omega^2)}$	$\begin{cases} \dfrac{b^3}{(b-c)(d-b)(b^2+\omega^2)}e^{-bt} + \dfrac{c^3}{(c-d)(d-c)(c^2+\omega^2)}e^{-ct} \\ + \dfrac{d^3}{(d-b)(c-d)(d^2+\omega^2)}e^{-dt} \\ - \dfrac{\omega^2}{\sqrt{(b^2+\omega^2)(c^2+\omega^2)(d^2+\omega^2)}}\cos(\omega t - \phi) \\ \phi = \tan^{-1}\left(\dfrac{\omega}{b}\right) + \tan^{-1}\left(\dfrac{\omega}{c}\right) + \tan^{-1}\left(\dfrac{\omega}{d}\right) \end{cases}$
114.	$\dfrac{s^3}{(s+b)^2(s^2+\omega^2)}$	$\begin{cases} -\dfrac{b^3}{b^2+\omega^2}te^{-bt} + \dfrac{b^2(b^2+3\omega^2)}{(b^2+\omega^2)^2}e^{-bt} - \dfrac{\omega^2}{(b^2+\omega^2)}\sin(\omega t + \phi) \\ \phi = \tan^{-1}\left(\dfrac{b}{\omega}\right) - \tan^{-1}\left(\dfrac{\omega}{b}\right) \end{cases}$
115.	$\dfrac{s^2}{s^4+4\omega^4}$	$\cos(\omega t)\cosh(\omega t)$
116.	$\dfrac{s^3}{s^4-\omega^4}$	$\dfrac{1}{2}\left[\cosh(\omega t) + \cos(\omega t)\right]$
117.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s^2(s+b)(s+c)}$	$\begin{cases} \dfrac{a_o}{bc}t - \dfrac{a_o(b+c)-a_1bc}{b^2c^2} + \dfrac{-b^3+a_2b^2-a_1b+a_o}{b^2(c-b)}e^{-bt} \\ + \dfrac{-c^3+a_2c^2-a_1c+a_o}{c^2(b-c)}e^{-ct} \end{cases}$
118.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)}$	$\begin{cases} \dfrac{a_o}{bcd} - \dfrac{-b^3+a_2b^2-a_1b+a_o}{b(c-b)(d-b)}e^{-bt} - \dfrac{-c^3+a_2c^2-a_1c+a_o}{c(b-c)(d-c)}e^{-ct} \\ - \dfrac{-d^3+a_2d^2-a_1d+a_o}{d(b-d)(c-d)}e^{-dt} \end{cases}$
119.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s^2(s+b)(s+c)(s+d)}$	$\begin{cases} \dfrac{a_o}{bcd}t + \left[\dfrac{a_1}{bcd} - \dfrac{a_o(bc+bd+cd)}{b^2c^2d^2}\right] + \dfrac{-b^3+a_2b^2-a_1b+a_o}{b^2(c-b)(d-b)}\varepsilon^{-bt} \\ + \dfrac{-c^3+a_2c^2-a_1c+a_o}{c^2(b-c)(d-c)}e^{-ct} + \dfrac{-d^3+a_2d^2-a_1d+a_o}{d^2(b-d)(c-d)}e^{-dt} \end{cases}$
120.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)(s+f)}$	$\begin{cases} \dfrac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)(f-b)}e^{-bt} + \dfrac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)(f-c)}e^{-ct} \\ + \dfrac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)(f-d)}e^{-dt} + \dfrac{-f^3+a_2f^2-a_1f+a_o}{(b-f)(c-f)(d-f)}e^{-ft} \end{cases}$
121.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)(s+f)}$	$\begin{cases} \dfrac{a_o}{bcdf} - \dfrac{-b^3+a_2b^2-a_1b+a_o}{b(c-b)(d-b)(f-b)}e^{-bt} - \dfrac{-c^3+a_2c^2-a_1c+a_o}{c(b-c)(d-c)(f-c)}e^{-ct} \\ - \dfrac{d^3+a_2d^2-a_1d+a_o}{d(b-d)(c-d)(f-d)}e^{-dt} - \dfrac{-f^3+a_2f^2-a_1f+a_o}{f(b-f)(c-f)(d-f)}e^{-ft} \end{cases}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
122.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)(s+f)(s+g)}$	$\dfrac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)(f-b)(g-b)}e^{-bt}+\dfrac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)(f-c)(g-c)}e^{-ct}+\dfrac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)(f-d)(g-d)}e^{-dt}+\dfrac{-f^3+a_2f^2-a_1f+a_o}{(b-f)(c-f)(d-f)(g-f)}e^{-ft}+\dfrac{-g^3+a_2g^2-a_1g+a_o}{(b-c)(c-g)(d-g)(f-g)}e^{-gt}$
123.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)^2}$	$\dfrac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)^2}e^{-bt}+\dfrac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)^2}e^{-ct}+\dfrac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)}te^{-dt}+\dfrac{a_o(2d-b-c)+a_1(bc-d)^2+a_2d(db+dc-2bc)+d^2(d^2-2db-2dc+3bc)}{(b-d)^2(c-d)^2}e^{-dt}$
124.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{s(s+b)(s+c)(s+d)^2}$	$\dfrac{a_o}{bcd^2}-\dfrac{-b^3+a_2b^2-a_1b+a_o}{b(c-b)(d-b)^2}e^{-bt}-\dfrac{-c^3+a_2c^2-a_1c+a_o}{c(b-c)(d-c)^2}e^{-ct}-\dfrac{-d^3+a_2d^2-a_1d+a_o}{d(b-d)(c-d)}te^{-dt}-\dfrac{3d^2-2a_2d+a_1}{d(b-d)(c-d)}e^{-dt}-\dfrac{(d^3+a_2d^2-a_1d+a_o)[(b-d)(c-d)-d(b-d)-d(c-d)]}{d^2(b-d)^2(c-d)^2}e^{-dt}$ z
125.	$\dfrac{s^3+a_2s^2+a_1s+a_o}{(s+b)(s+c)(s+d)(s+f)^2}$	$\dfrac{-b^3+a_2b^2-a_1b+a_o}{(c-b)(d-b)(f-b)^2}e^{-bt}+\dfrac{-c^3+a_2c^2-a_1c+a_o}{(b-c)(d-c)(f-c)^2}e^{-ct}+\dfrac{-d^3+a_2d^2-a_1d+a_o}{(b-d)(c-d)(f-d)^2}e^{-dt}+\dfrac{-f^3+a_2f^2-a_1f+a_o}{(b-f)(c-f)(d-f)}te^{-ft}+\dfrac{3f^2-2a_2f+a_1}{(b-f)(c-f)(d-f)}e^{-ft}-\dfrac{(-f^3+a_2f^2-a_1f+a_o)[(b-f)(c-f)+(b-f)(d-f)+(c-f)(d-f)]}{(b-f)^2(c-f)^2(d-f)^2}e^{-ft}$
126.	$\dfrac{s}{(s-a)^{3/2}}$	$\dfrac{1}{\sqrt{\pi t}}e^{at}(1+2at)$
127.	$\sqrt{s-a}-\sqrt{s-b}$	$\dfrac{1}{2\sqrt{\pi t^3}}\left(e^{bt}-e^{at}\right)$
128.	$\dfrac{1}{\sqrt{s}+a}$	$\dfrac{1}{\sqrt{\pi t}}-ae^{a^2t}erfc\left(a\sqrt{t}\right)$
129.	$\dfrac{\sqrt{s}}{s-a^2}$	$\dfrac{1}{\sqrt{\pi t}}+ae^{a^2t}erf\left(a\sqrt{t}\right)$
130.	$\dfrac{\sqrt{s}}{s+a^2}$	$\dfrac{1}{\sqrt{\pi t}}-\dfrac{2a}{\sqrt{\pi}}e^{-a^2t}\int_0^{a\sqrt{t}}e^{\lambda^2}d\lambda$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
131.	$\frac{1}{\sqrt{s}\left(s-a^2\right)}$	$\frac{1}{a}e^{a^2t}erf\left(a\sqrt{t}\right)$
132.	$\frac{1}{\sqrt{s}\left(s+a^2\right)}$	$\frac{2}{a\sqrt{\pi}}e^{-a^2t}\int_0^{a\sqrt{t}}e^{\lambda^2}d\pi$
133.	$\frac{b^2-a^2}{\left(s-a^2\right)\left(b+\sqrt{s}\right)}$	$e^{a^2t}\left[b-a\,erf\left(a\sqrt{t}\right)\right]-be^{b^2t}erfc\left(b\sqrt{t}\right)$
134.	$\frac{1}{\sqrt{s}\left(\sqrt{s}+a\right)}$	$e^{a^2t}erfc\left(a\sqrt{t}\right)$
135.	$\frac{1}{(s+a)\sqrt{s+b}}$	$\frac{1}{\sqrt{b-a}}e^{-at}erf\left(\sqrt{b-a}\sqrt{t}\right)$
136.	$\frac{b^2-a^2}{\sqrt{s}\left(s-a^2\right)\left(\sqrt{s}+b\right)}$	$e^{a^2t}\left[\frac{b}{a}erf\left(a\sqrt{t}\right)-1\right]+e^{b^2t}erfc\left(b\sqrt{t}\right)$
137.	$\frac{(1-s)^n}{s^{n+(1/2)}}$	$\begin{cases}\frac{n!}{(2n)!\sqrt{nt}}H_{2n}\left(\sqrt{t}\right)\\ \left[H_n(t)=\text{Hermite polynomial}=e^{x^2}\frac{d^n}{dx^n}\left(e^{-x^2}\right)\right]\end{cases}$
138.	$\frac{(1-s)^n}{s^{n+(3/2)}}$	$-\frac{n!}{\sqrt{\pi}(2n+1)!}H_{2n+1}\left(\sqrt{t}\right)$
139.	$\frac{\sqrt{s+2a}}{\sqrt{s}}-1$	$\begin{cases}ae^{-at}\left[I_1(at)+I_o(at)\right]\\ \left[I_n(t)=j^{-n}J_n(jt)\text{ where }J_n\text{ is Bessel's function of the first kind}\right]\end{cases}$
140.	$\frac{1}{\sqrt{s+a}\sqrt{s+b}}$	$e^{-(1/2)(a+b)t}I_o\left(\frac{a-b}{2}t\right)$
141.	$\frac{\Gamma(k)}{(s+a)^k(s+b)^k}\quad(k\geq 0)$	$\sqrt{\pi}\left(\frac{t}{a-b}\right)^{k-(1/2)}e^{-(1/2)(a+b)t}I_{k-(1/2)}\left(\frac{a-b}{2}t\right)$
142.	$\frac{1}{(s+a)^{1/2}(s+b)^{3/2}}$	$te^{-(1/2)(a+b)t}\left[I_o\left(\frac{a=b}{2}t\right)+I_1\left(\frac{a-b}{2}t\right)\right]$
143.	$\frac{\sqrt{s+2a}-\sqrt{s}}{\sqrt{s+2a}+\sqrt{s}}$	$\frac{1}{t}e^{-at}I_1(at)$
144.	$\frac{(a-b)^k}{\left(\sqrt{s+a}+\sqrt{s+b}\right)^{2k}}\quad(k>0)$	$\frac{k}{t}e^{-(1/2)(a+b)t}I_k\left(\frac{a-b}{2}t\right)$
145.	$\frac{\left(\sqrt{s+a}+\sqrt{s}\right)^{-2v}}{\sqrt{s}\sqrt{s+a}}$	$\frac{1}{a^v}e^{-(1/2)(at)}I_v\left(\frac{1}{2}at\right)$
146.	$\frac{1}{\sqrt{s^2+a^2}}$	$J_o(at)$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
147.	$\dfrac{\left(\sqrt{s^2+a^2}-s\right)^{\nu}}{\sqrt{s^2+a^2}} \quad (\nu>-1)$	$a^{\nu}J_{\nu}(at)$
148.	$\dfrac{1}{\left(s^2+a^2\right)^k} \quad (k>0)$	$\dfrac{\sqrt{\pi}}{\Gamma(k)}\left(\dfrac{t}{2a}\right)^{k-(1/2)} J_{k-(1/2)}(at)$
149.	$\left(\sqrt{s^2+a^3}-s\right)^{\mathbf{k}} \quad (k>0)$	$\dfrac{ka^k}{t}J_k(at)$
150.	$\dfrac{\left(s-\sqrt{s^2-a^2}\right)^{\nu}}{\sqrt{s^2-a^2}} \quad (\nu>-1)$	$a^{\nu}I_{\nu}(at)$
151.	$\dfrac{1}{\left(s^2-a^2\right)^k} \quad (k>0)$	$\dfrac{\sqrt{\pi}}{\Gamma(k)}\left(\dfrac{t}{2a}\right)^{k-(1/2)} I_{k-(1/2)}(at)$
152.	$\dfrac{1}{s\sqrt{s+1}}$	$erf\left(\sqrt{t}\right); erf(y)^{\Delta}$ the error function $= \dfrac{2}{\sqrt{\pi}}\int_o^y e^{-u^2}du$
153.	$\dfrac{1}{\sqrt{s^2+a^2}}$	$J_a(at)$; Bessel function of 1st kind, zero order
154.	$\dfrac{1}{\sqrt{s^2+a^2}+s}$	$\dfrac{J_1(at)}{at}$; J_1 is the Bessel function of 1st kind, 1st order
155.	$\dfrac{1}{\left[\sqrt{s^2+a^2}+s\right]^N}$	$\dfrac{N}{a^N}\dfrac{J_N(at)}{t}$; $N = 1,2,3,\cdots$, J_N is the Bessel function of 1st kind, Nth order
156.	$\dfrac{1}{s\left[\sqrt{s^2+a^2}+s\right]^N}$	$\dfrac{N}{a^N}\int_o^t \dfrac{J_N(au)}{u}du$; $N = 1,2,3,\cdots$, J_N is the Bessel function of 1st kind, Nth order
157.	$\dfrac{1}{\sqrt{s^2+a^2}\left(\sqrt{s^2+a^2}+s\right)}$	$\dfrac{1}{a}J_1(at)$; J_1 is the Bessel function of lst kind, lst order
158.	$\dfrac{1}{\sqrt{s^2+a^2}\left[\sqrt{s^2+a^2}+s\right]^N}$	$\dfrac{1}{a^N}J_N(at)$; $N = 1,2,3,\cdots$, J_N is the Bessel function of lst kind, Nth order
159.	$\dfrac{1}{\sqrt{s^2-a^2}}$	$I_o(at)$; I_o is the modified Bessel function of 1st kind, zero order
160.	$\dfrac{e^{-ks}}{s}$	$S_k(t)=\begin{cases}0 & when\ 0<t<k\\ 1 & when\ t>k\end{cases}$
161.	$\dfrac{e^{-ks}}{s^2}$	$\begin{cases}0 & when\ 0<t<k\\ t-k & when\ t>k\end{cases}$
162.	$\dfrac{e^{-ks}}{s^{\mu}} \quad (\mu>0)$	$\begin{cases}0 & when\ 0<t<k\\ \dfrac{(t-k)^{\mu-1}}{\Gamma(\mu)} & when\ t>k\end{cases}$
163.	$\dfrac{1-e^{-ks}}{s}$	$\begin{cases}1 & when\ 0<t<k\\ 0 & when\ t>k\end{cases}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
164.	$\frac{1}{s(1-e^{-ks})}=\frac{1+\coth\frac{1}{2}ks}{2s}$	$S(k,t)=\begin{cases} n & \text{when} \\ & (n-1)k<t<n \quad k(n=1,2,\cdots) \end{cases}$
165.	$\frac{1}{s(e^{+ks}-a)}$	$S_k(t)=\begin{cases} 0 & \text{when } 0<t<k \\ 1+a+a^2+\cdots+a^{n-1} \\ \text{when } nk<t<(n+k)k(n=1,2,\cdots) \end{cases}$
166.	$\frac{1}{s}\tanh ks$	$\begin{cases} M(2k,t)=(-1)^{n-1} \\ \quad \text{when } 2k(n-1)<t<2nk \\ \quad (n=1,2,\cdots) \end{cases}$
167.	$\frac{1}{s(1+e^{-ks})}$	$\begin{cases} \frac{1}{2}M(k,t)+\frac{1}{2}=\frac{1-(1-1)^n}{2} \\ \quad \text{when } (n-1)k<t<nk \end{cases}$
168.	$\frac{1}{s^2}\tanh ks$	$\begin{cases} H(2k,t) \quad \left[H(2k,t)=k+(r-k)(-1)^n \quad \text{where } t=2kn+r; \right. \\ \quad \left. 0\le r\le 2k; n=0,1,2,\cdots\right] \end{cases}$
169.	$\frac{1}{s\sinh ks}$	$\begin{cases} 2S(sk,t+k)-2=2(n-1) \\ \quad \text{when } (2n-3)k<t<(2n-1)k(t>0) \end{cases}$
170.	$\frac{1}{s\cosh ks}$	$\begin{cases} M(2k,t+3k)+1=1+(-1)^n \\ \quad \text{when } (2n-3)k<t<(2n-1)k(t>0) \end{cases}$
171.	$\frac{1}{s}\coth ks$	$\begin{cases} 2S(2k,t)-1=2n-1 \\ \quad \text{when } 2k(n+1)<t<2kn \end{cases}$
172.	$\frac{k}{s^2+k^2}\coth\frac{\pi s}{2k}$	$\lvert\sin kt\rvert$
173.	$\frac{1}{(s^2+1)(1-e^{-\pi s})}$	$\begin{cases} \sin t & \text{when } (2n-2)\pi<t<(2n-1)\pi \\ 0 & \text{when } (2n-1)\pi<t<2n\pi \end{cases}$
174.	$\frac{1}{s}e^{-k/s}$	$J_o(2\sqrt{kt})$
175.	$\frac{1}{\sqrt{s}}e^{-k/s}$	$\frac{1}{\sqrt{\pi t}}\cos 2\sqrt{kt}$
176.	$\frac{1}{\sqrt{s}}e^{k/s}$	$\frac{1}{\sqrt{\pi t}}\cosh 2\sqrt{kt}$
177.	$\frac{1}{s^{3/2}}e^{-k/s}$	$\frac{1}{\sqrt{\pi k}}\sin 2\sqrt{kt}$
178.	$\frac{1}{s^{3/2}}e^{k/s}$	$\frac{1}{\sqrt{\pi k}}\sinh 2\sqrt{kt}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
179.	$\frac{1}{s^{\mu}}e^{-k/s} \quad (\mu > 0)$	$\left(\frac{t}{k}\right)^{(\mu-1)/2} J_{\mu-1}\left(2\sqrt{kt}\right)$
180.	$\frac{1}{s^{\mu}}e^{k/s} \quad (\mu > 0)$	$\left(\frac{t}{k}\right)^{(\mu-1)/2} I_{\mu-1}\left(2\sqrt{kt}\right)$
181.	$e^{-k\sqrt{s}} \quad (k > 0)$	$\frac{k}{2\sqrt{\pi t^3}}\exp\left(-\frac{k^2}{4t}\right)$
182.	$\frac{1}{s}e^{-k\sqrt{s}} \quad (k \geq 0)$	$erfc\left(\frac{k}{2\sqrt{t}}\right)$
183.	$\frac{1}{\sqrt{s}}e^{-k\sqrt{s}} \quad (k \geq 0)$	$\frac{1}{\sqrt{\pi t}}\exp\left(-\frac{k^2}{4t}\right)$
184.	$s^{-3/2}e^{-k\sqrt{s}} \quad (k \geq 0)$	$2\sqrt{\frac{1}{\pi}}\exp\left(-\frac{k^2}{4t}\right) - k\, erfc\left(\frac{k}{2\sqrt{t}}\right)$
185.	$\frac{ae^{-k\sqrt{s}}}{s\left(a+\sqrt{s}\right)} \quad (k \geq 0)$	$-e^{ak}e^{a^2t}\, erfc\left(a\sqrt{t} + \frac{k}{2\sqrt{t}}\right) + erfc\left(\frac{k}{2\sqrt{t}}\right)$
186.	$\frac{e^{-k\sqrt{s}}}{\sqrt{s}\left(a+\sqrt{s}\right)} \quad (k \geq 0)$	$e^{ak}e^{a^2t}\, erfc\left(a\sqrt{t} + \frac{k}{2\sqrt{t}}\right)$
187.	$\frac{e^{-k\sqrt{s(s+a)}}}{\sqrt{s(s+a)}}$	$\begin{cases} 0 & when\ 0 < t < k \\ e^{-(1/2)at} I_o\left(\frac{1}{2}a\sqrt{t^2-k^2}\right) & when\ t > k \end{cases}$
188.	$\frac{e^{-k\sqrt{s^2+a^2}}}{\sqrt{\left(s^2+a^2\right)}}$	$\begin{cases} 0 & when\ 0 < t < k \\ J_o\left(a\sqrt{t^2-k^2}\right) & when\ t > k \end{cases}$
189.	$\frac{e^{-k\sqrt{s^2-a^2}}}{\sqrt{\left(s^2-a^2\right)}}$	$\begin{cases} 0 & when\ 0 < t < k \\ I_o\left(a\sqrt{t^2-k^2}\right) & when\ t > k \end{cases}$
190.	$\frac{e^{-k\left(\sqrt{s^2+a^2}-s\right)}}{\sqrt{\left(s^2+a^2\right)}} \quad (k \geq 0)$	$J_o\left(a\sqrt{t^2+2kt}\right)$
191.	$e^{-ks} - e^{-k\sqrt{s^2+a^2}}$	$\begin{cases} 0 & when\ 0 < t < k \\ \frac{ak}{\sqrt{t^2-k^2}} J_1\left(a\sqrt{t^2-k^2}\right) & when\ t > k \end{cases}$
192.	$e^{-k\sqrt{s^2+a^2}} - e^{-ks}$	$\begin{cases} 0 & when\ 0 < t < k \\ \frac{ak}{\sqrt{t^2-k^2}} I_1\left(a\sqrt{t^2-k^2}\right) & when\ t > k \end{cases}$
193.	$\frac{a^{\nu}e^{-k\sqrt{s^2-a^2}}}{\sqrt{\left(s^2+a^2\right)}\left(\sqrt{s^2+a^2}+s\right)^{\nu}} \quad (\nu > -1)$	$\begin{cases} 0 & when\ 0 < t < k \\ \left(\frac{t-k}{t+k}\right)^{(1/2)\nu} J_{\nu}\left(a\sqrt{t^2-k^2}\right) & when\ t > k \end{cases}$
194.	$\frac{1}{s}\log s$	$\Gamma'(l) - \log t \; [\Gamma'(1) = -0.5772]$

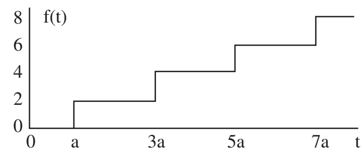
Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
195.	$\frac{1}{s^k}\log s \quad (k>0)$	$t^{k-1}\left\{\frac{\Gamma'(k)}{[\Gamma(k)]^2}\frac{\log t}{\Gamma(k)}\right\}$
196.	$\frac{\log s}{s-a} \quad (a>0)$	$e^{at}[\log a - \mathrm{Ei}(-at)]$
197.	$\frac{\log s}{s^2+1}$	$\cos t\,\mathrm{Si}(t) - \sin t\,\mathrm{Ci}(t)$
198.	$\frac{s\log s}{s+1}$	$-\sin t\,\mathrm{Si}(t) - \mathrm{cost}\, t\,\mathrm{Ci}(t)$
199.	$\frac{1}{s}\log(1+ks) \quad (k>0)$	$-\mathrm{Ei}\left(-\frac{t}{k}\right)$
200.	$\log\frac{s-a}{s-b}$	$\frac{1}{t}\left(e^{bt}-e^{at}\right)$
201.	$\frac{1}{s}\log\left(1+k^2s^2\right)$	$-2\mathrm{Ci}\left(\frac{t}{k}\right)$
202.	$\frac{1}{s}\log\left(s^2+a^2\right) \quad (a>0)$	$2\log a - 2\mathrm{Ci}(at)$
203.	$\frac{1}{s^2}\log\left(s^2+a^2\right) \quad (a>0)$	$\frac{2}{a}\left[at\log a + \sin at - at\,\mathrm{Ci}(at)\right]$
204.	$\log\frac{s^2+a^2}{s^2}$	$\frac{2}{t}(1-\cos at)$
205.	$\log\frac{s^2-a^2}{s^2}$	$\frac{2}{t}(1-\cosh at)$
206.	$\arctan\frac{k}{s}$	$\frac{1}{t}\sin kt$
207.	$\frac{1}{s}\arctan\frac{k}{s}$	$\mathrm{Si}(kt)$
208.	$e^{k^2s^2}\,erfc(ks) \quad (k>0)$	$\frac{1}{k\sqrt{\pi}}\exp\left(-\frac{t^2}{4k^2}\right)$
209.	$\frac{1}{s}e^{k^2s^2}\,erfc(ks) \quad (k>0)$	$erf\left(\frac{t}{2k}\right)$
210.	$e^{ks}\,erfc\left(\sqrt{ks}\right) \quad (k>0)$	$\frac{\sqrt{k}}{\pi\sqrt{t(t+k)}}$
211.	$\frac{1}{\sqrt{s}}\,erfc\left(\sqrt{ks}\right)$	$\begin{cases}0 & \text{when } 0<t<k \\ (\pi t)^{-1/2} & \text{when } t>k\end{cases}$
212.	$\frac{1}{\sqrt{s}}e^{ks}\,erfc\left(\sqrt{ks}\right) \quad (k>0)$	$\frac{1}{\sqrt{\pi(t+k)}}$
213.	$erf\left(\frac{k}{\sqrt{s}}\right)$	$\frac{1}{\pi t}\sin\left(2k\sqrt{t}\right)$
214.	$\frac{1}{\sqrt{s}}e^{k^2/s}\,erfc\left(\frac{k}{\sqrt{s}}\right)$	$\frac{1}{\sqrt{\pi t}}e^{-2k\sqrt{t}}$

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
215.	$-e^{as}\mathrm{Ei}(-as)$	$\frac{1}{t+a}$; $(a>0)$
216.	$\frac{1}{a}+se^{as}Ei(-as)$	$\frac{1}{(t+a)^2}$; $(a>0)$
217.	$\left[\frac{\pi}{2}-\mathrm{Si}(s)\right]\cos s+\mathrm{Ci}(s)\sin s$	$\frac{1}{t^2+1}$
218.	$K_o(ks)$	$\begin{cases}0 & \text{when } 0<t<k\\ (t^2-k^2)^{-1/2} & \text{when } t>k\end{cases}$ $\left[K_n(t)\right.$ is Bessel function of the second kind of imaginary argument$\left.\right]$
219.	$K_o(k\sqrt{s})$	$\frac{1}{2t}\exp\left(-\frac{k^2}{4t}\right)$
220.	$\frac{1}{s}e^{ks}K_1(ks)$	$\frac{1}{k}\sqrt{t(t+2k)}$
221.	$\frac{1}{\sqrt{s}}K_1(k\sqrt{s})$	$\frac{1}{k}\exp\left(-\frac{k^2}{4t}\right)$
222.	$\frac{1}{\sqrt{s}}e^{k/s}K_o\left(\frac{k}{s}\right)$	$\frac{2}{\sqrt{\pi t}}K_o(2\sqrt{2kt})$
223.	$\pi e^{-ks}I_o(ks)$	$\begin{cases}[t(2k-t)]^{-1/2} & \text{when } 0<t<2k\\ 0 & \text{when } t>2k\end{cases}$
224.	$e^{-ks}I_1(ks)$	$\begin{cases}\frac{k-t}{\pi k\sqrt{t(2k-t)}} & \text{when } 0<t<2k\\ 0 & \text{when } t>2k\end{cases}$

225. $\frac{1}{s\sinh(as)}$ — $f(t)$: $2\sum_{k=0}^{\infty} u\,[t-(2k+1)a]$



226. $\frac{1}{s\cosh s}$ — $f(t)$: $2\sum_{k=0}^{\infty} (-1)^k\,u\,(t-2k-1)$

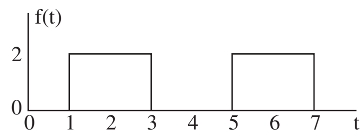
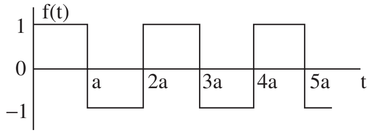


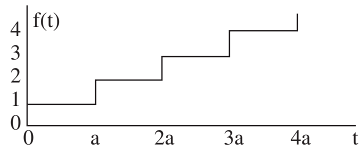
Table of Laplace Transforms (continued)

	F(*s*)	*f*(*t*)
227.	$\frac{1}{s}\tanh\left(\frac{as}{2}\right)$	$u(t) + 2\sum_{k=1}^{\infty}(-1)^k u\,(t-ak)$ square wave
228.	$\frac{1}{2s}\left(1+\coth\frac{as}{2}\right)$	$\sum_{k=0}^{\infty} u(t-ak)$ stepped function
229.	$\frac{m}{s^2}-\frac{ma}{2s}\left(\coth\frac{as}{2}-1\right)$	$mt - ma\sum_{k=1}^{\infty} u(t-ka)$ saw – tooth function
230.	$\frac{1}{s^2}\tanh\left(\frac{as}{2}\right)$	$\frac{1}{a}\left[t + 2\sum_{k=1}^{\infty}(-1)^k (t-ka)\,.\,u(t-ka)\right]$ triangular wave

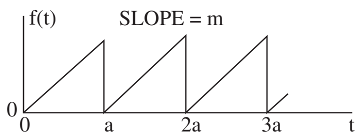
227. square wave



228. stepped function



229. saw – tooth function



230. triangular wave

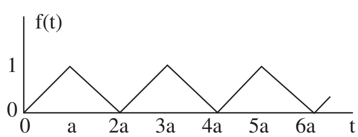
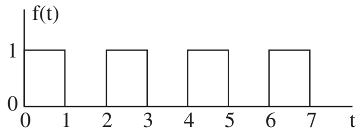


Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$

231. $\dfrac{1}{s\left(1+e^{-s}\right)}$

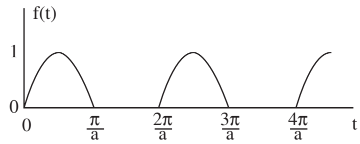
$$\sum_{k=0}^{\infty} (-1)^k u\,(t-k)$$



232. $\dfrac{a}{\left(s^2+a^2\right)\left(1-e^{-\frac{\pi}{a}s}\right)}$

$$\sum_{k=0}^{\infty} \left[\sin a\left(t-k\,\frac{\pi}{a}\right)\right].\,u\left(t-k\,\frac{\pi}{a}\right)$$

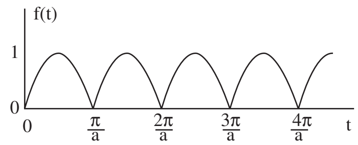
half – wave rectification of sine wave



233. $\left[\dfrac{a}{\left(s^2+a^2\right)}\right]\coth\left(\dfrac{\pi s}{2a}\right)$

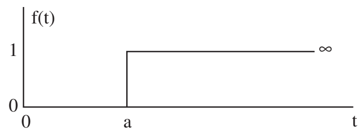
$$[\sin\ (at)]\cdot u\,(t) + 2\sum_{k=1}^{\infty}\left[\sin a\left(t-k\,\frac{\pi}{a}\right)\right]\cdot u\left(t-k\frac{\pi}{a}\right)$$

full – wave rectification of sine wave



234. $\dfrac{1}{s}e^{-as}$

$u\,(t-a)$



235. $\dfrac{1}{s}\left(e^{-as}-e^{-bs}\right)$

$u\,(t-a) - u\,(t-b)$

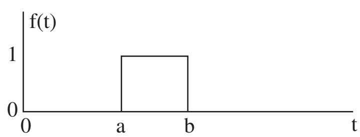


Table of Laplace Transforms (continued)

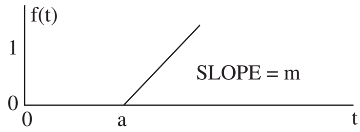
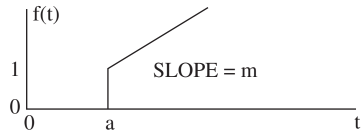
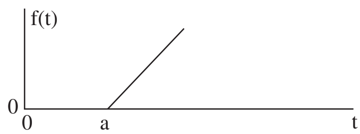
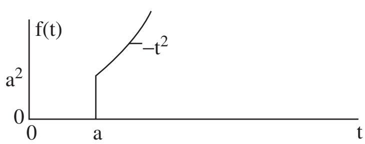
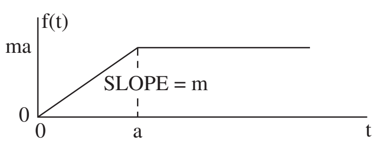
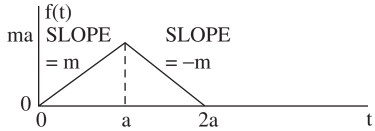
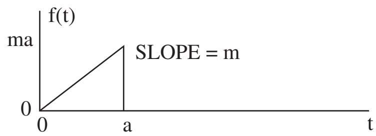
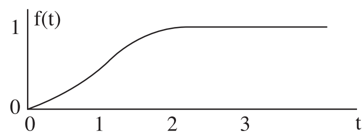
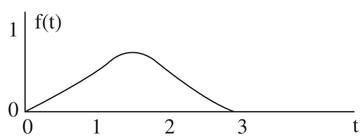
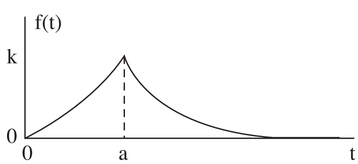
	$F(s)$	$f(t)$
236.	$\frac{m}{s^2}e^{-as}$	$m \cdot (t-a) \cdot u\,(t-a)$ 
237.	$\left[\frac{ma}{s}+\frac{m}{s^2}\right]e^{-as}$	$mt \cdot u(t-a)$ or $[ma + m\,(t-a)] \cdot u(t-a)$ 
238.	$\frac{2}{s^3}e^{-as}$	$(t-a)^2 \cdot u(t-a)$ 
239.	$\left[\frac{2}{s^3}+\frac{2a}{s^2}+\frac{a^2}{s}\right]e^{-as}$	$t^2 \cdot u(t-a)$ 
240.	$\frac{m}{s^2}-\frac{m}{s^2}e^{-as}$	$mt \cdot u(t) - m(t-a) \cdot u(t-a)$ 

Table of Laplace Transforms (continued)

	$F(s)$	$f(t)$
241.	$\frac{m}{s^2}-\frac{2m}{s^2}e^{-as}+\frac{m}{s^2}e^{-2as}$	$mt-2m(t-a)\cdot u(t-a)+m(t-2a)\cdot u(t-2a)$ 
242.	$\frac{m}{s^2}-\left(\frac{ma}{s}+\frac{m}{s^2}\right)e^{-as}$	$mt-[ma+m(t-a)]\cdot u(t-a)$ 
243.	$\frac{\left(1-e^{-s}\right)^2}{s^3}$	$0.5t^2$ for $0\le t<1$ $1-0.5(t-2)^2$ for $0\le t<2$ 1 for $2\le t$ 
244.	$\left[\frac{\left(1-e^{-s}\right)}{s}\right]^3$	$0.5t^2$ for $0\le t<1$ $0.75-(t-1.5)^2$ for $1\le t<2$ $0.5(t-3)^2$ for $2\le t<3$ 0 for $3<t$ 
245.	$\frac{b}{s(s-b)}+\left(e^{ba}-1\right)\left[\frac{1}{s+b}-\frac{s+\frac{b}{e^{ba}-1}}{s(s-b)}\right]e^{-as}$	$(e^{bt}-1)\cdot u(t)-(e^{bt}-1)\cdot u(t-a)+Ke^{-b(t-a)}\cdot u(t-a)$ where $K=(e^{ba}-1)$ 

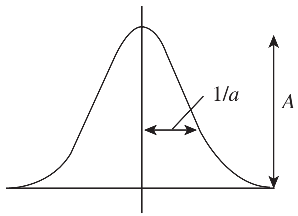
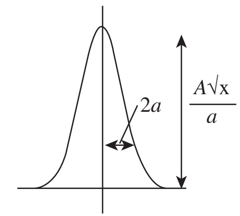
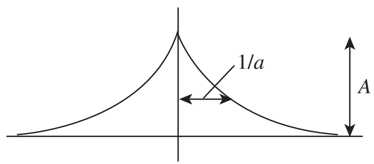
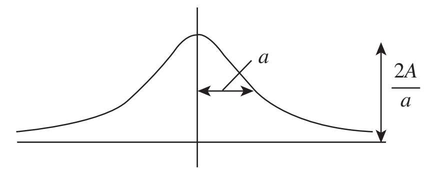
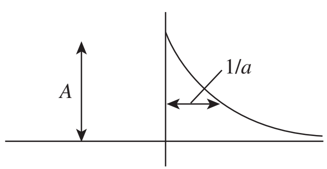
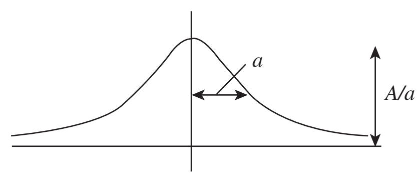
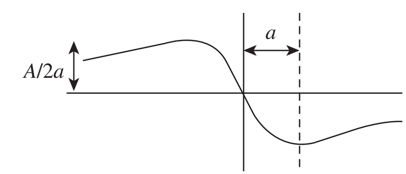
From Poularikas, A., Laplace transforms, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, pp. **2**-7 to **2**-23.

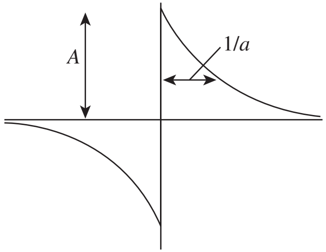
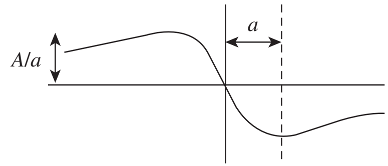
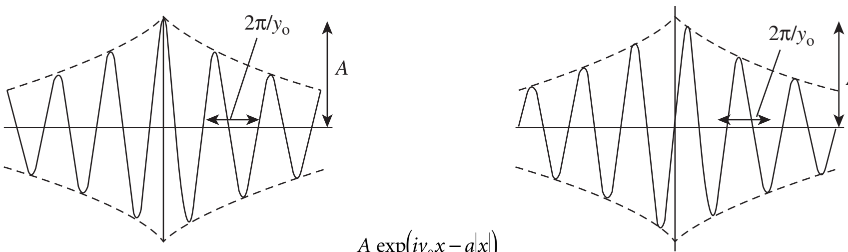
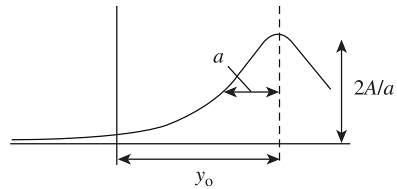
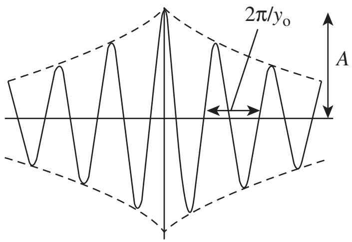
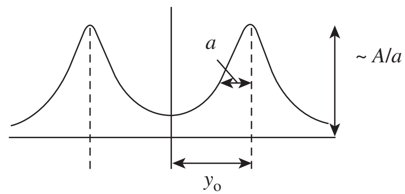
Properties of Fourier Transform

	Operation	$f(t)$	$F(\omega)$
1.	Transform-direct	$f(t)$	$\int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt$
2.	Inverse transform	$\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{j\omega t}d\omega$	$F(\omega)$
3.	Linearity	$af_1(t) + bf_2(t)$	$aF_1(\omega) + bF_2(\omega)$
4.	Symmetry	$F(t)$	$2\pi f(-\omega)$
5.	Time shifting	$f(t \pm t_o)$	$e^{\pm j\omega t_o}F(\omega)$
6.	Scaling	$f(at)$	$\frac{1}{\lvert a\rvert}F\left(\frac{\omega}{a}\right)$
7.	Frequency shifting	$e^{\pm j\omega_o t}f(t)$	$F(\omega \mp \omega_o)$
8.	Modulation	$\begin{cases} f(t)\cos\omega_o t \\ f(t)\sin\omega_o t \end{cases}$	$\frac{1}{2}\left[F(\omega+\omega_o)+F(\omega-\omega_o)\right]$ $\frac{1}{2j}\left[F(\omega-\omega_o)-F(\omega+\omega_o)\right]$
9.	Time differentiation	$\frac{d^n}{dt^n}f(t)$	$(j\omega)^n F(\omega)$
10.	Time convolution	$f(t)*h(t)=\int_{-\infty}^{\infty} f(\tau)h(t-\tau)d\tau$	$F(\omega)\ H(\omega)$
11.	Frequency convolution	$f(t)\ h(t)$	$\frac{1}{2\pi}F(\omega)*H(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\tau)H(\omega-\tau)d\tau$
12.	Autocorrelation	$f(t)\star f^*(t)=\int_{-\infty}^{\infty} f(\tau)f^*(\tau-t)d\tau$	$F(\omega)\ F^*(\omega) = \lvert F(\omega)\rvert^2$
13.	Parseval's formula	$E=\int_{-\infty}^{\infty} \lvert f(t)\rvert^2 dt$	$E=\frac{1}{2\pi}\int_{-\infty}^{\infty} \lvert F(\omega)\rvert^2 d\omega$
14.	Moments formula	$m_n=\int_{-\infty}^{\infty} t^n f(t)dt=\frac{F^{(n)}(0)}{(-j)^n}$ where	$F^{(n)}(0)=\left.\frac{d^n F(\omega)}{d\omega^n}\right\rvert_{\omega=0}, \quad n=0,1,2\cdots$
15.	Frequency differentiation	$\begin{cases} (-jt)f(t) \\ (-jt)^n f(t) \end{cases}$	$\frac{dF(\omega)}{d\omega}$ $\frac{d^n F(\omega)}{d\omega^n}$
16.	Time reversal	$f(-t)$	$F(-\omega)$
17.	Conjugate function	$f^*(t)$	$F^*(-\omega)$
18.	Integral ($F(0) = 0$)	$\int_{-\infty}^{t} f(t)dt$	$\frac{1}{j\omega}F(\omega)$
19.	Integral ($F(0) \neq 0$)	$\int_{-\infty}^{t} f(t)dt$	$\frac{1}{j\omega}F(\omega)+\pi F(0)\delta(\omega)$

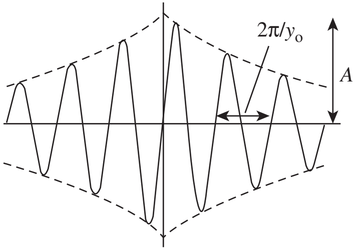
From Poularikas, A., Fourier transformation, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, pp. **3**-3.

Table of Fourier Transforms ($x = t$, $y = w$)

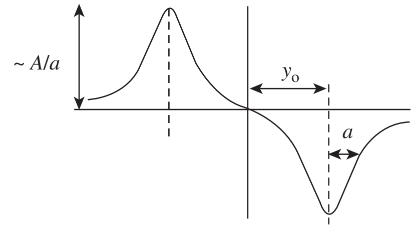
$f(x)$ $\left[f(x) = (1/2\pi)\int_{-\infty}^{+\infty} F(y)e^{+ixy}\mathrm{d}y\right]$	$F(y)$ $\left[F(y) = \int_{-\infty}^{+\infty} f(x)e^{-ixy}\mathrm{d}x\right]$
 $A\exp(-a^2x^2)$ [Gaussian]	 $\frac{A\sqrt{\pi}}{a}\exp(-y^2/4a^2)$ [Gaussian]
 $A\exp(-a\lvert x\rvert)$	$\frac{2A}{a}\,\frac{a^2}{a^2+y^2}$ [Lorentzian] 
 $A\exp(-ax)$ $[x>0]$ 0 $[x<0]$	  $A\left\{\frac{a-iy}{a^2+y^2}\right\}$

$f(x)$	$F(y)$
 $A\exp(-ax) \quad [x>0]$ $-A\exp(-a\lvert x\rvert) \quad [x<0]$	 $-2iA\dfrac{y}{a^2+y^2}$
 $A\exp(iy_0x - a\lvert x\rvert)$	 $\dfrac{2A}{a}\dfrac{a^2}{a^2+(y-y_0)^2}$
 $A\cos y_0x\exp(-a\lvert x\rvert)$	 $\dfrac{A}{a}\left\{\dfrac{a^2}{a^2+(y-y_0)^2}+\dfrac{a^2}{a^2+(y+y_0)^2}\right\}$ $=\dfrac{A}{a}\left\{\dfrac{2a^2(a^2+y_0{}^2+y^2)}{(a^2+y_0^2-y^2)^2+4a^2y^2}\right\}$

$f(x)$	$F(y)$

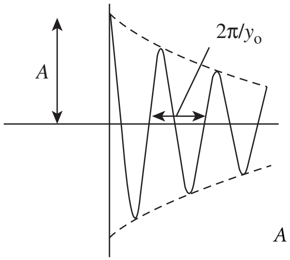


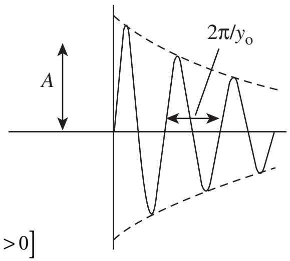
$A \sin y_0 x \exp(-a|x|)$



$$\frac{iA}{a}\left\{\frac{a^2}{a^2+(y+y_0)^2}-\frac{a^2}{a^2+(y-y_0)^2}\right\}$$

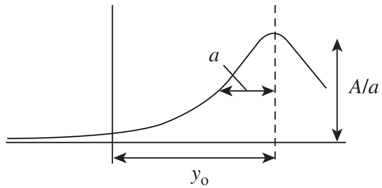
$$=\frac{iA}{a}\left\{\frac{-4a^2yy_0}{(a^2+y_0^2-y^2)^2+4a^2y^2}\right\}$$

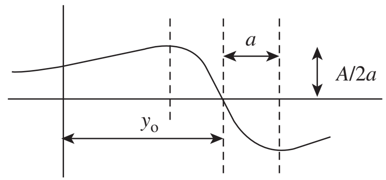




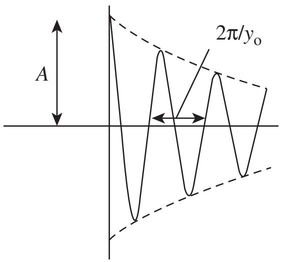
$A \exp(iy_0x - ax)$ $[x > 0]$

0 $[x < 0]$



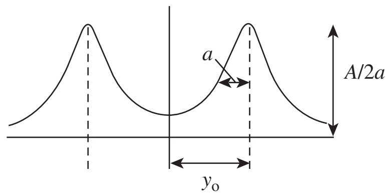


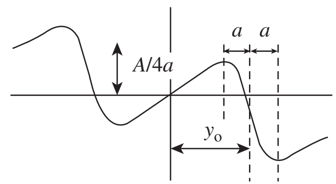
$$A\left\{\frac{a+i(y_0-y)}{a^2+(y_0-y)^2}\right\}=A\left\{\frac{1}{a+i(y-y_0)}\right\}$$



$A \cos y_0 x \exp(-ax)$ $[x > 0]$

0 $[x < 0]$

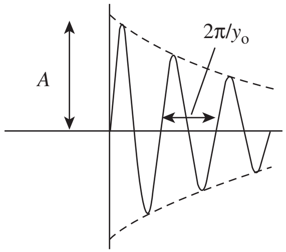




$$\frac{A}{2}\left[\left\{\frac{a}{a^2+(y+y_0)^2}+\frac{a}{a^2+(y-y_0)^2}\right\}+i\left\{\frac{y_0-y}{a^2+(y_0-y)^2}-\frac{y_0+y}{a^2+(y_0+y)^2}\right\}\right]$$

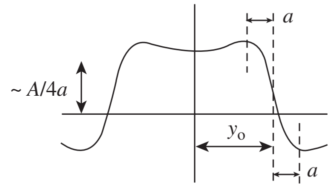
$$=A\left\{\frac{a(a^2+y_0^2+y^2)-iy(a^2+y^2-y_0^2)}{(a^2+y_0^2-y^2)^2+4a^2y^2}\right\}$$

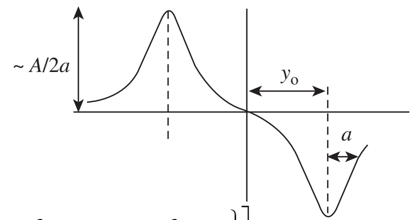
$f(x)$	$F(y)$



$A \sin y_0 x \exp(-ax)$ $[x > 0]$

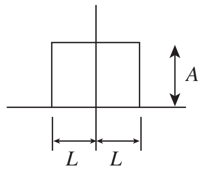
0 $[x < 0]$





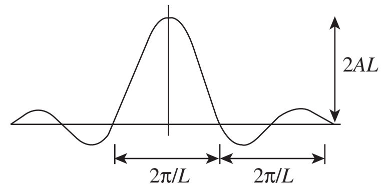
$$\frac{A}{2}\left[\left\{\frac{y_0-y}{a^2+(y_0-y)^2}+\frac{y_0+y}{a^2+(y_0+y)^2}\right\}+i\left\{\frac{a}{a^2+(y_0+y)^2}-\frac{a}{a^2+(y_0-y)^2}\right\}\right]$$

$$= Ay_0\left\{\frac{1}{(a^2+y_0^2-y^2)+i2ay}\right\}$$

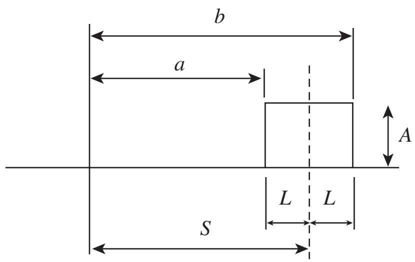


A $[|x| < L]$

0 $[|x| > L]$

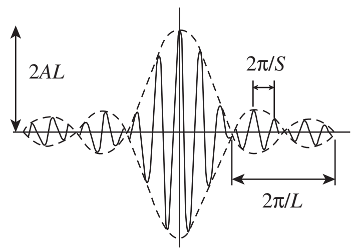


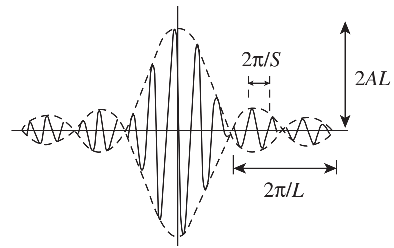
$$2A\frac{\sin Ly}{y}$$



A $[a < x < b]$

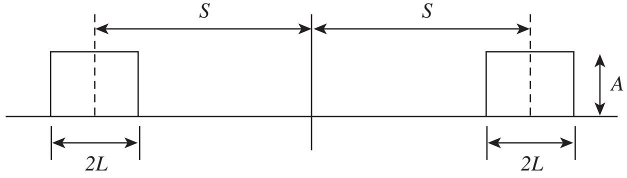
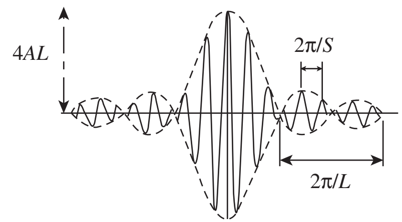
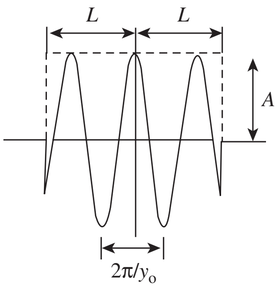
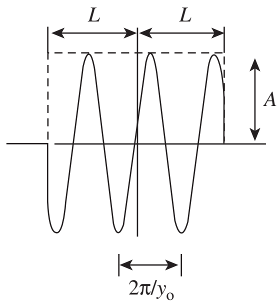
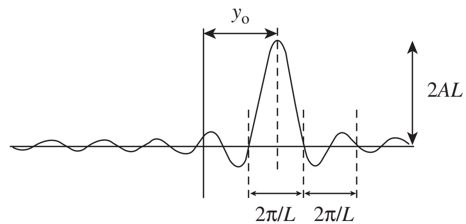
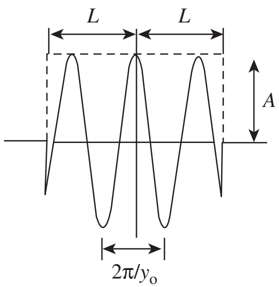
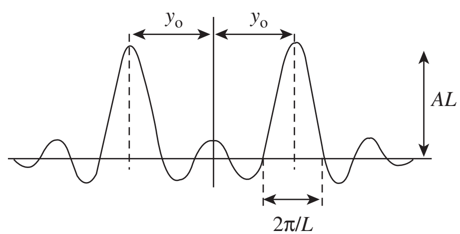
0 $[x < a;\ x > b]$





$$2A\frac{\sin Ly}{y}\exp(-iSy) = A\left[\frac{(\sin by - \sin ay) - i(\cos ay - \cos by)}{y}\right]$$

$$= 2A\left[\frac{(\sin Ly \cos Sy) - i(\sin Ly \sin Sy)}{y}\right] = \frac{iA}{y}\left[\exp(-iby) - \exp(-iay)\right]$$

$f(x)$	$F(y)$
 $A \quad [(S-L) < \lvert x\rvert < (S+L)]$ $0 \quad [\text{otherwise}]$	 $4A\dfrac{\cos Sy \sin Ly}{y}$
 $A\exp(iy_0x) \quad [\lvert x\rvert < L]$ $0 \quad [\lvert x\rvert > L]$ 	 $2A\dfrac{\sin\{L(y_0-y)\}}{(y_0-y)}$
 $A\cos y_0x \quad [\lvert x\rvert < L]$ $0 \quad [\lvert x\rvert > L]$	 $A\left[\dfrac{\sin L(y-y_0)}{(y-y_0)} + \dfrac{\sin L(y+y_0)}{(y+y_0)}\right]$

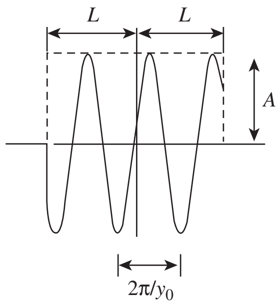
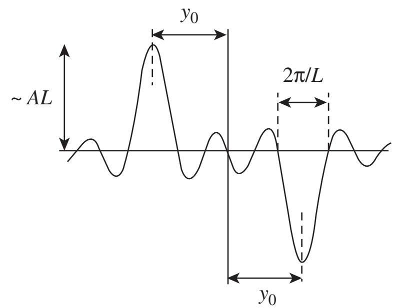
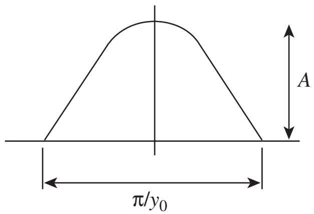
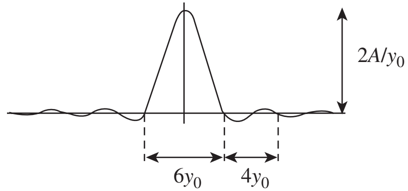
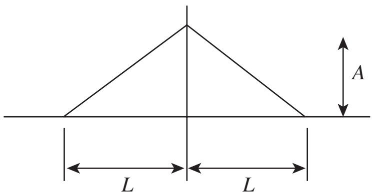
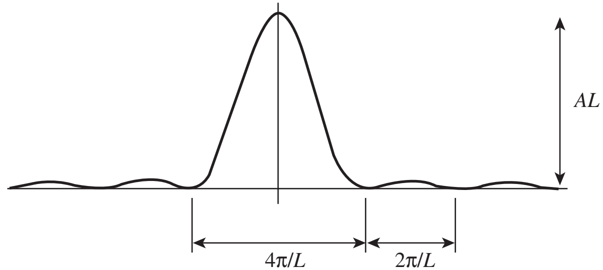
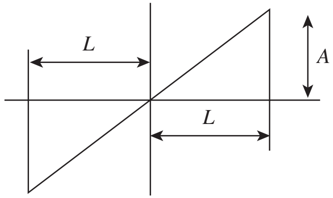
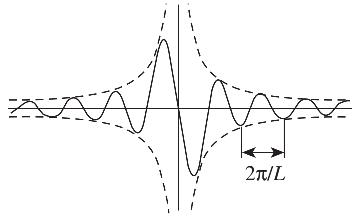
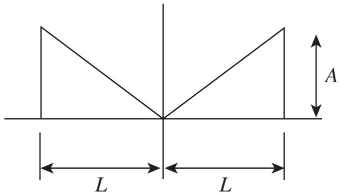
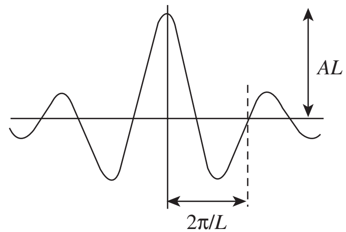
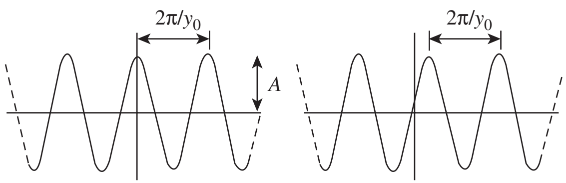
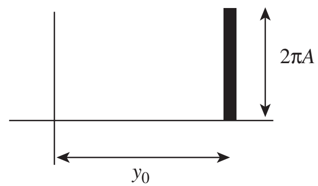
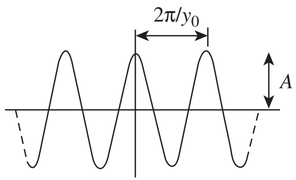
$f(x)$		$F(y)$	
	$A \sin y_0 x \quad [\lvert x \rvert < L]$ $0 \quad [\lvert x \rvert > L]$		$iA\left\{\frac{\sin L(y+y_0)}{(y+y_0)} - \frac{\sin L(y-y_0)}{(y-y_0)}\right\}$
	$A \cos y_0 x \quad [\lvert x \rvert < (\pi/2y_0)]$ $0 \quad [\lvert x \rvert > (\pi/2y_0)]$		$2A\left(\frac{y_0}{y_0^2 - y^2}\right)\cos\left(\frac{\pi y}{2y_0}\right)$
	$A\left(1 - \frac{\lvert x \rvert}{L}\right) \quad [\lvert x \rvert < L]$ $0 \quad [\lvert x \rvert > L]$		$AL\left(\frac{\sin(Ly/2)}{(Ly/2)}\right)^2$

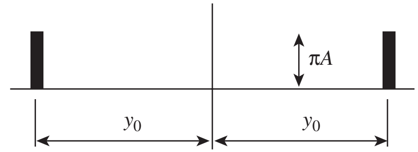
Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$	$F(y)$
	
$\frac{Ax}{L} \quad [\lvert x\rvert < L]$ $0 \quad [\lvert x\rvert > L]$	$\frac{2iA}{y}\left(\cos Ly - \frac{\sin Ly}{Ly}\right)$
	
$\frac{A\lvert x\rvert}{L} \quad [\lvert x\rvert < L]$ $0 \quad [\lvert x\rvert > L]$	$2AL\left\{\frac{\sin Ly}{Ly} - 2\left(\frac{\sin(Ly/2)}{Ly}\right)^2\right\}$
	
$A\exp(iy_0x)$	$2xA\delta(y - y_0)$

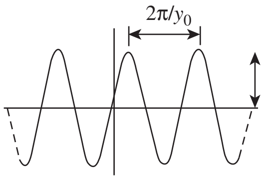
$f(x)$	$F(y)$



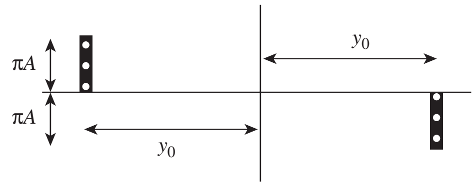
$A \cos y_0 x$



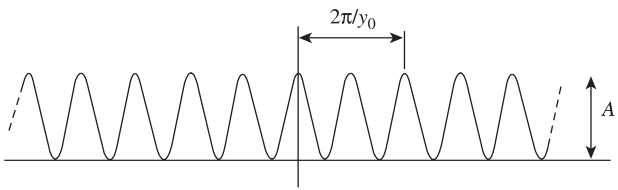
$$xA\{\delta(y - y_0) + \delta(y + y_0)\}$$



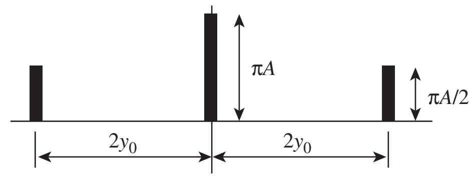
$A \sin y_0 x$



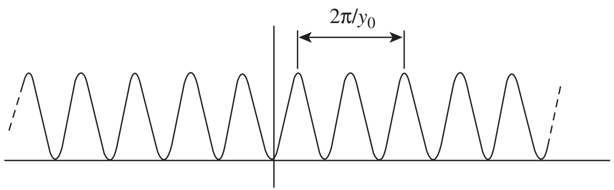
$$\pi i A\{\delta(y + y_0) - \delta(y - y_0)\}$$



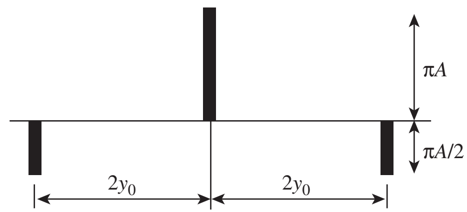
$A \sin^2 y_0 x$



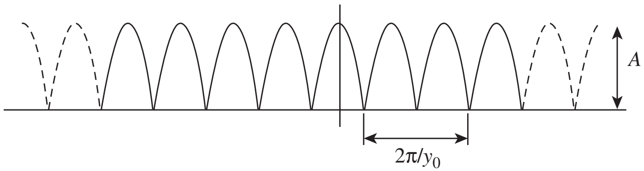
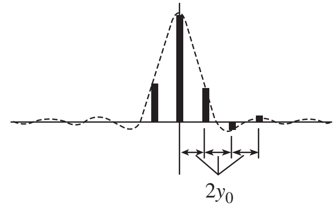
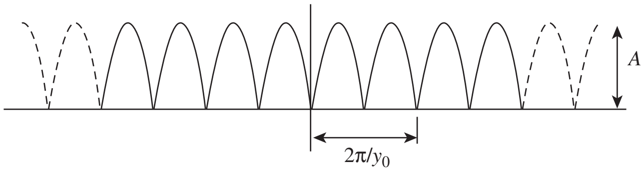
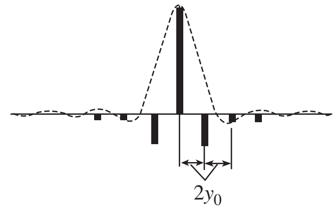
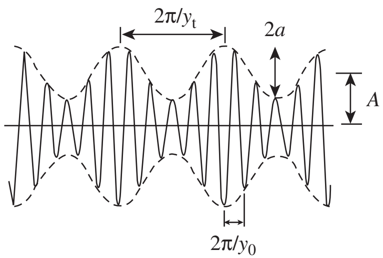
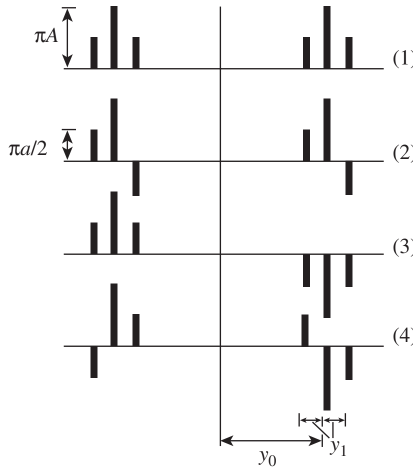
$$\pi A\{-\tfrac{1}{2}\delta(y + 2y_0) + \delta(y) + \tfrac{1}{2}\delta(y - 2y_0)\}$$

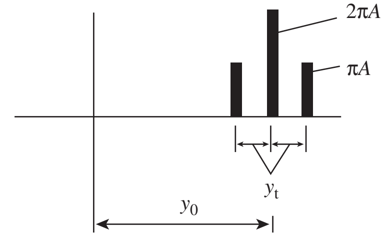
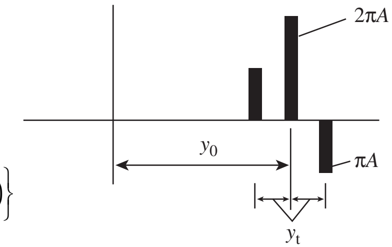


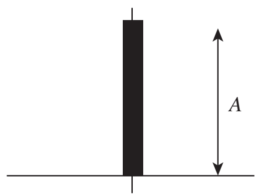
$A \sin^2 y_0 x$

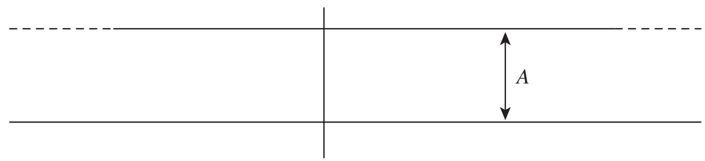


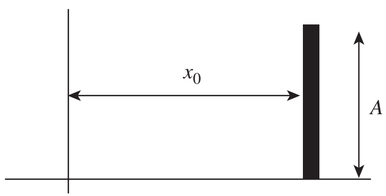
$$\pi A\{-\tfrac{1}{2}\delta(y + 2y_0) + \delta(y) - \tfrac{1}{2}\delta(y - 2y_0)\}$$

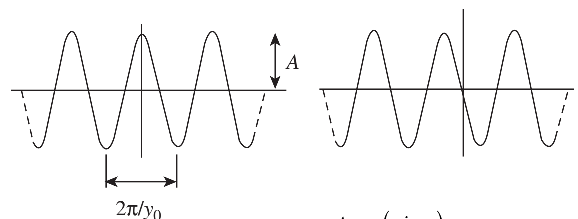
$f(x)$	$F(y)$
 $A\lvert\cos y_0 x\rvert$	$\sum_{n^{\pi y}-\infty}^{n^{\pi y}+\infty} 4A\left(\frac{y_0^2}{y_0^2-y^2}\right)\cos\left(\frac{xy}{2y_0}\right)\delta\left(y-2\pi y_0\right)$ $\left[n=0,\pm 1,\pm 2,\ldots\right]$ 
 $A\left[\sin y_0 x\right]$	$\sum_{n^{\pi y}-\infty}^{n^{\pi y}+\infty} (-1)^a 4A\left(\frac{y_0^2}{y_0^2-y^2}\right)\cos\left(\frac{xy}{2y_0}\right)\delta\left(y-2\pi y_0\right)$ $\left[n=0,\pm 1,\pm 2,\ldots\right]$ 
 $\cos y_0 x\left[A+a\cos y_1 x\right]\ldots(1)$ $\cos y_0 x\left[A+a\sin y_1 x\right]\ldots(2)$ $\sin y_0 x\left[A+a\cos y_1 x\right]\ldots(3)$ $\sin y_0 x\left[A+a\sin y_1 x\right]\ldots(4)$	 $F(y)$ consists of delta functions as shown

<table>
<tr><th>$f(x)$</th><th>$F(y)$</th></tr>
<tr><td>$\exp(iy_0x)(A + a\cos y_1x)$</td><td>$$2\pi\left\{A\delta(y-y_0)+\frac{a}{2}\delta(y-y_0+y_1)+\frac{a}{2}\delta(y-y_0-y_1)\right\}$$

</td></tr>
<tr><td>$\exp(iy_0x)(A + a\sin y_1x)$</td><td>

$$2\pi\left\{A\delta(y-y_0)+\frac{ia}{2}\delta(y-y_0+y_1)-\frac{ia}{2}\delta(y-y_0-y_1)\right\}$$</td></tr>
<tr><td>

$A\delta(x)$</td><td>

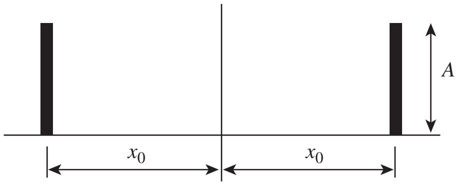
A</td></tr>
<tr><td>

$A\delta(x-x_0)$</td><td>

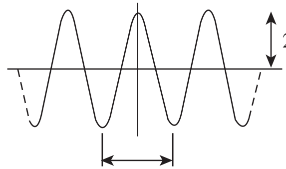
$A\exp(-ix_0y)$</td></tr>
</table>

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

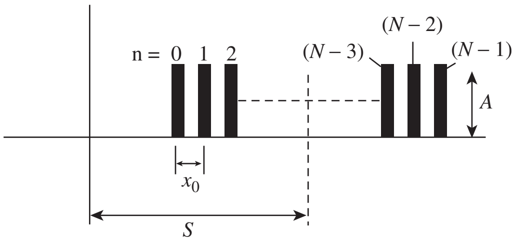
f(x) → F(y)



$A\{\delta(x-x_0)+\delta(x+x_0)\}$

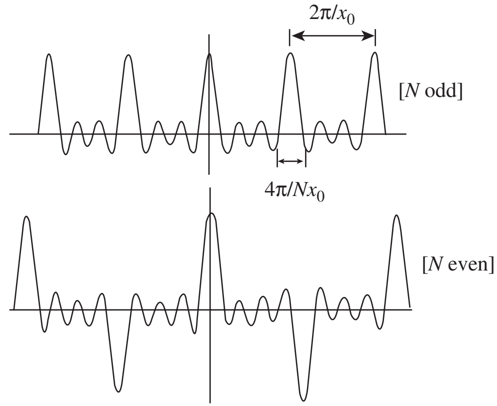


$2A\cos x_0 y$

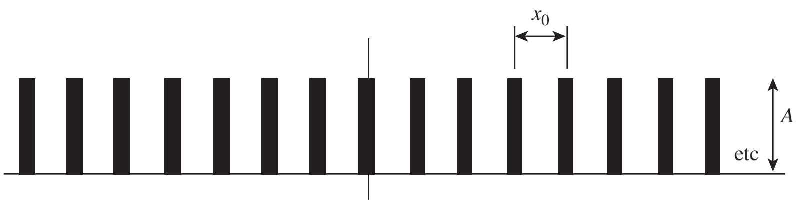


$$\sum_{n=0}^{N-1} A\delta\left\{x - nx_0 - S + \frac{(N-1)x_0}{2}\right\}$$

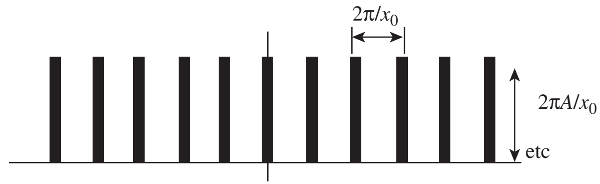
Set of N delta functions symmetrically placed about $x = S$.



$A\dfrac{\sin(Nyx_0/2)}{\sin(yx_0/2)}\exp(-iSy)$ [Drawn for $S = 0$; $N = 7$ and $N = 8$]



$$\sum_{n^{x_0}-\infty}^{+\infty} A\delta(x - nx_0)$$



$$\sum_{n^{x_0}-\infty}^{+\infty} \frac{2\pi A}{x_0}\delta\left(y - n\frac{2\pi}{x_0}\right)$$

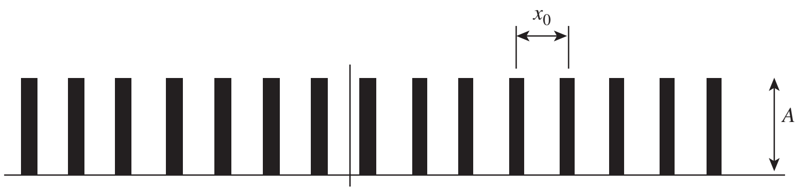
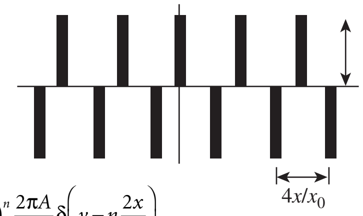
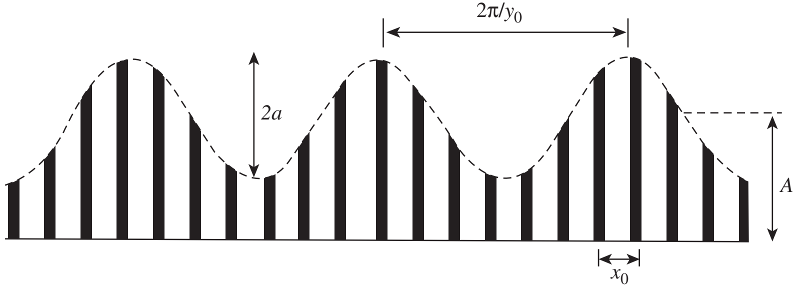
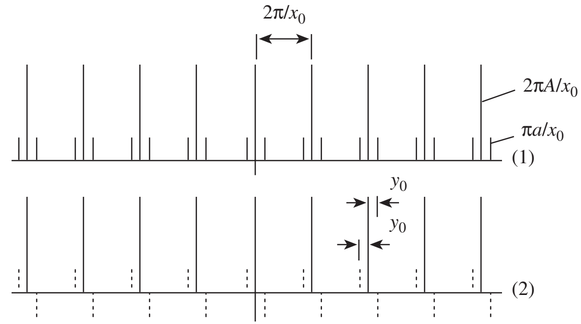
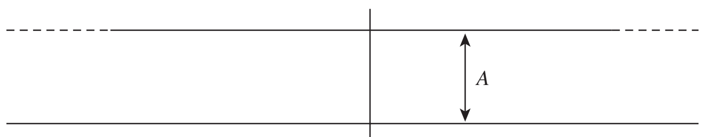
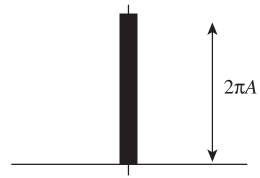
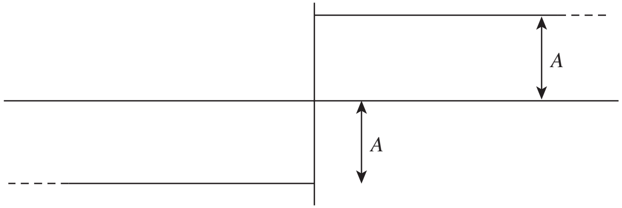
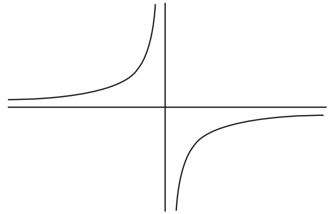
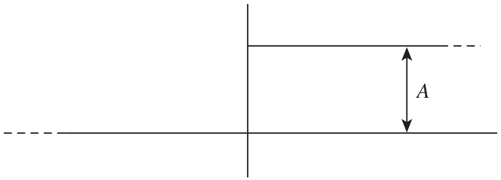
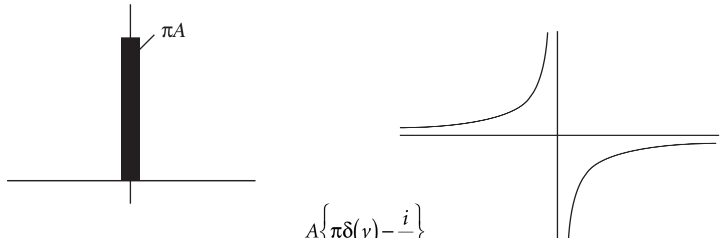
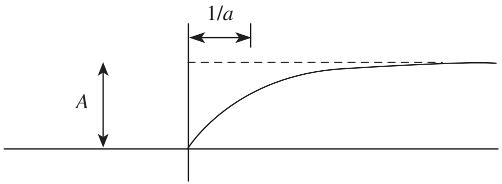
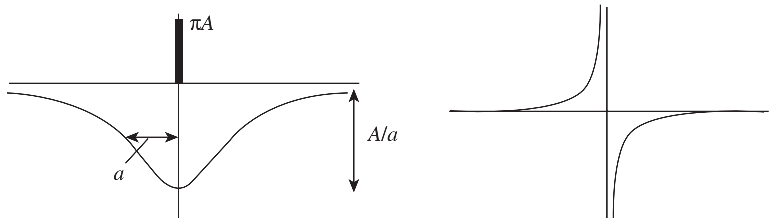
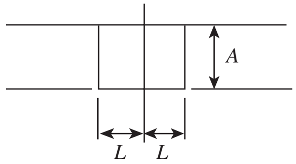
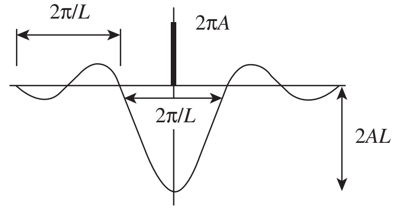
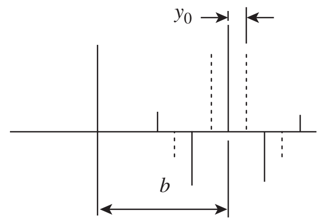
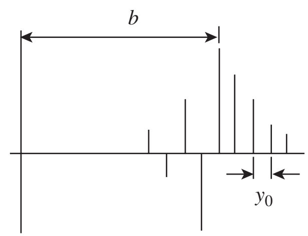
$f(x)$	$F(y)$
 $\sum_{n^{x_0-\infty}}^{+\infty} A\delta\left(x-\frac{x_0}{2}-nx_0\right)$	 $\sum_{n^{x_0-\infty}}^{+\infty} (-1)^n \frac{2\pi A}{x_0}\delta\left(y-n\frac{2x}{x_0}\right)$
 $\sum \delta(x-nx_0)\{A+a\cos y_0x\}$ (1) $\sum \delta(x-nx_0)\{A+a\sin y_0x\}$ (2) $[n=0, \ \pm 1, \pm 2, \ldots]$	 $\sum_n \frac{2\pi}{x_0}\left\{A\delta\left(y-n\frac{2\pi}{x_0}\right)+\frac{a}{2}\delta\left(y-n\frac{2\pi}{x_0}+y_0\right)+\frac{a}{2}\delta\left(y-\frac{2\pi}{x_0}-y_0\right)\right\}$ $\sum_n \frac{2\pi}{x_0}\left\{A\delta\left(y-n\frac{2\pi}{x_0}\right)+\frac{ia}{2}\delta\left(y-n\frac{2\pi}{x_0}+y_0\right)-\frac{ia}{2}\delta\left(y-n\frac{2\pi}{x_0}-y_0\right)\right\}$ $[n=0, \pm 1, \pm 2, \ldots]$
 A	 $2\pi A\delta(y)$

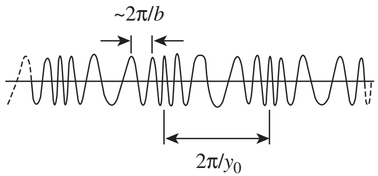
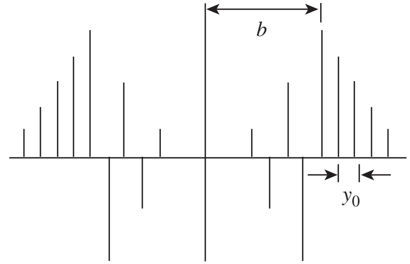
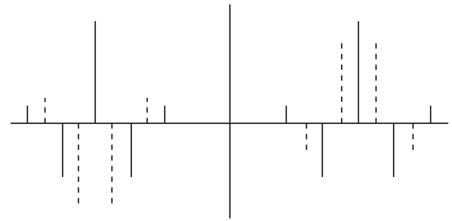
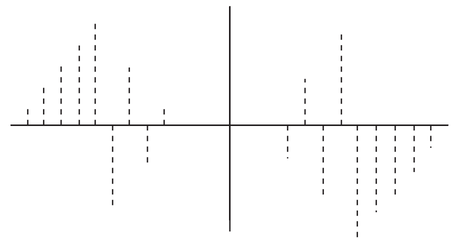
Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$	$F(y)$
 $\begin{matrix} +A & [x>0] \\ -A & [x<0] \end{matrix}\; [f(x) = A\,\mathrm{sgn}(x)]$	 $-2iA\dfrac{1}{y}$
 $\begin{matrix} A & [x>0] \\ 0 & [x<0] \end{matrix}\; [f(x) = AU(x)]$	 $A\left\{\pi\delta(y) - \dfrac{i}{y}\right\}$
 $\begin{matrix} A\{1-\exp(-ax)\} & [x>0] \\ 0 & [x<0] \end{matrix}$	 $\pi A\delta(y) - A\left\{\dfrac{a}{a^2+y^2} + i\dfrac{a^2}{y(a^2+y^2)}\right\}$

$f(x)$	$F(y)$
 $A \quad [\lvert x\rvert > L]$ $0 \quad [\lvert x\rvert < L]$	 $2\pi A\delta(y) - 2A\frac{\sin Ly}{y}$
$A \exp\{i(a \cos y_0 x + bx)\}$	 $2\pi A \sum_{n=-\infty}^{+\infty} (i)^n J_n(a)\delta(y - b - ny_0)$
$A \exp\{i(a \sin y_0 x + bx)\}$	 $2\pi A \sum_{n=-\infty}^{+\infty} J_n(a)\delta(y - b - ny_0)$

Note: $J_n(-a) = J_{-n}(a) = (-1)^n J_n(a)$.

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$	$F(y)$
 $A\cos(a\sin y_0x + bx)$	 $\pi A\sum_{n=-\infty}^{+\infty}\left\{J_n(a)\delta(y-b-ny_0)+J_n(a)\delta(y+b+ny_0)\right\}$
$A\cos(a\cos y_0x + bx)$	 $\pi A\sum_{n=-\infty}^{+\infty}\left\{(+i)^n J_n(a)\delta(y-b-ny_0)+(-i)^n J_n(a)\delta(y+b+ny_0)\right\}$
$A\sin(a\sin y_0x + bx)$	 $i\pi A\sum_{n=-\infty}^{+\infty}\left\{-J_n(a)\delta(y-b-ny_0)+J_n(a)\delta(y+b+ny_0)\right\}$

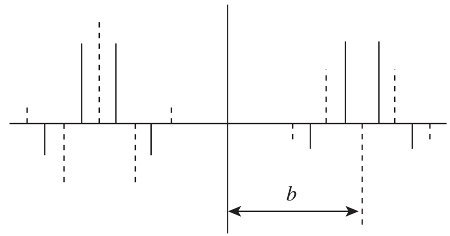
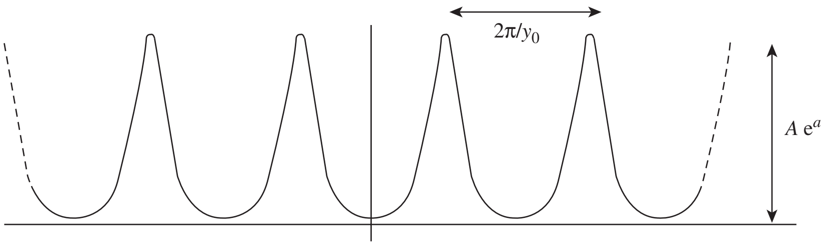
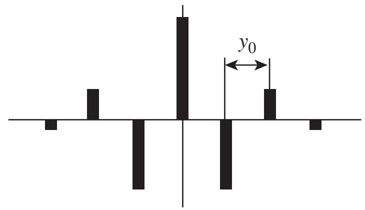
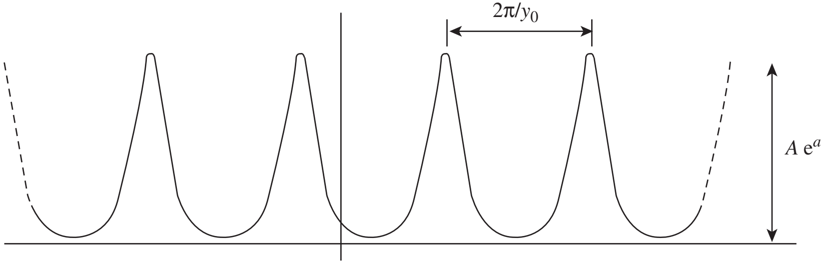
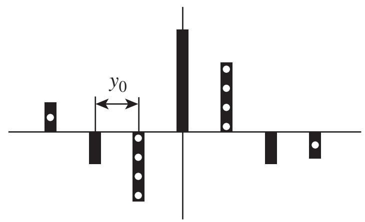
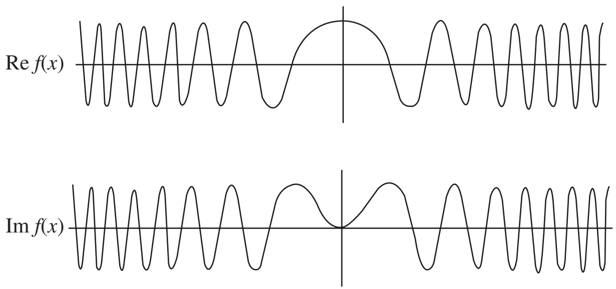
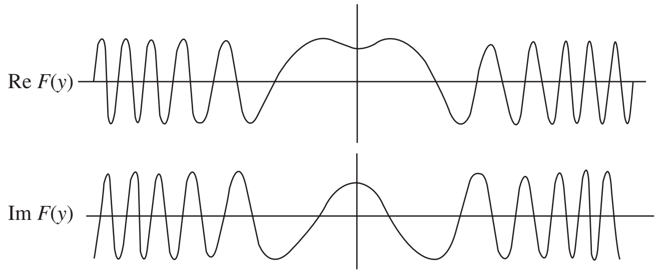
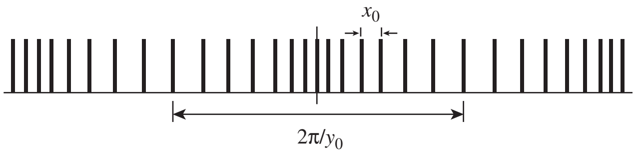
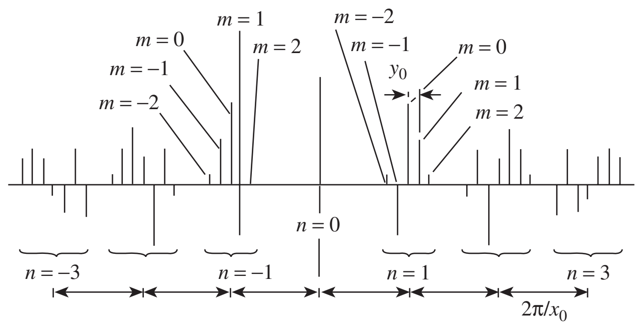
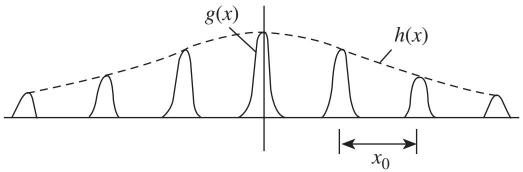
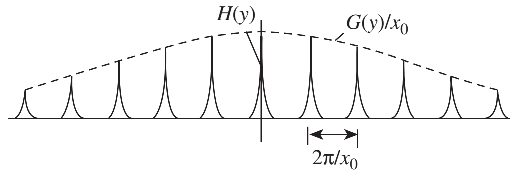
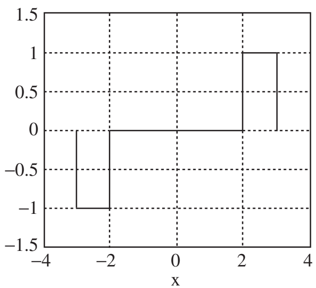
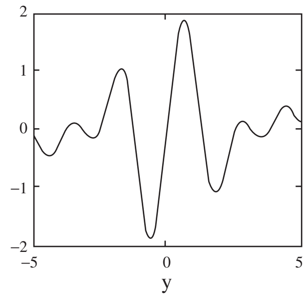
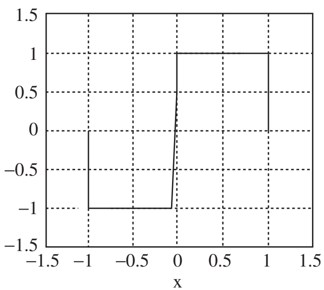
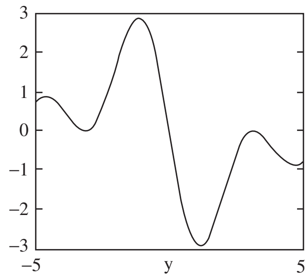
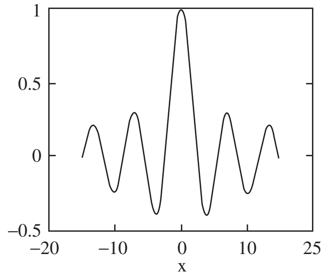
$f(x)$	$F(y)$
$A \sin(a \cos y_0 x + bx)$	 $i\pi A \sum_{n=-\infty}^{+\infty} \left\{ (-i)^n J_n(a)\delta(y-b-ny_0) + (-i)^n J_n(a)\delta(y+b+ny_0) \right\}$
 $A \exp(-a \cos y_0 x)$	 $2\pi A \sum_{n=-\infty}^{+\infty} (-1)^n I_n(a)\delta(y-ny_0)$
 $A \exp(-a \sin y_0 x)$	 $2\pi A \sum_{n=-\infty}^{+\infty} (i)^n I_n(a)\delta(y-ny_0)$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

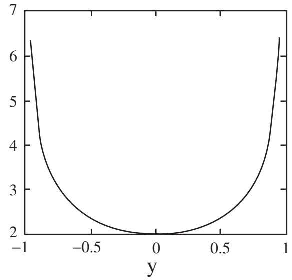
$f(x)$	$F(y)$
	
$A\exp\left(\pm i a^2 x^2\right)$	$\left(\frac{x}{2}\right)^{\frac{1}{2}}\frac{A(1-i)}{a}\exp\left(\mp i y^2/4a^2\right)$
	
$f(x)=A\sum_{n}\delta\left(x-nx_0+a\sin y_0x\right)$	$F(y)=\frac{2xA}{x_0}\sum_{m,n}J_m\left(n\frac{2\pi a}{x_0}\right)\delta\left(y-n\frac{2\pi}{x_0}-my_0\right)$ $(m=0,\ \pm1,\ \pm2,\ \pm3,\ \ldots)$ $(n=0,\ \pm1,\ \pm2,\ \pm3,\ \ldots)$

$f(x)$	$F(y)$
	
$f(x) = h(x)\sum_{n=-\infty}^{+\infty} g(x - nx_0)$	$F(y) = \frac{1}{x_0}\sum_{n=-\infty}^{+\infty}\left\{G\left(\frac{n2\pi}{x_0}\right)H\left(y - \frac{n2\pi}{x_0}\right)\right\}$
$f(x) = \sum_{n=-\infty}^{+\infty} h(nx_0)g(x - nx_0)$	$F(y) = \frac{1}{x_0}G(y)\sum_{n=-\infty}^{+\infty} H\left(y - \frac{n2\pi}{x_0}\right)$
 A $\quad s - a < x < s + a$ −A $\quad -s - a < x < -s + a$	 $-2Aj\frac{\sin ay}{y}\sin ys$
 A $\quad 0 < x < 2a$ −A $\quad -2a < x < 0$	 $-4jA\sin ay\frac{\sin ay}{y}$

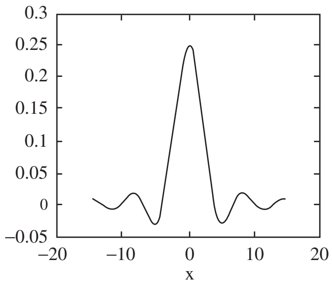
$f(x)$	$F(y)$
$J_0(x)$	$\frac{2}{\sqrt{1-y^2}}$
$\frac{J_1(x)}{2x}$	$\sqrt{1-y^2}$
$\frac{1}{\pi x}$	$\text{sqn } y = \begin{cases} 1 & y > 0 \\ 0 & y = 0 \\ -1 & y < 0 \end{cases}$



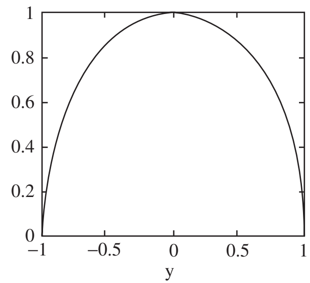
$J_0(x)$



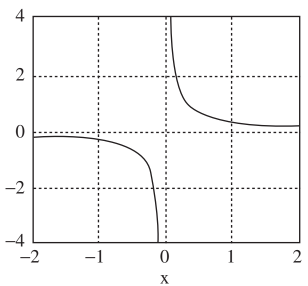
$$\frac{2}{\sqrt{1-y^2}}$$



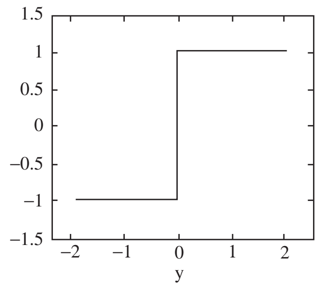
$$\frac{J_1(x)}{2x}$$



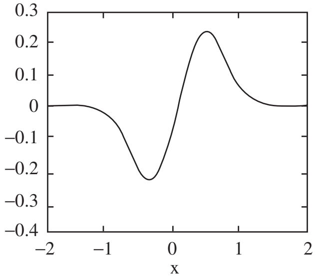
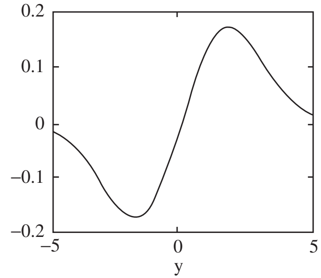
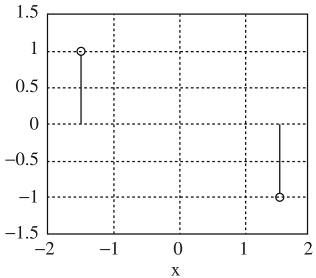
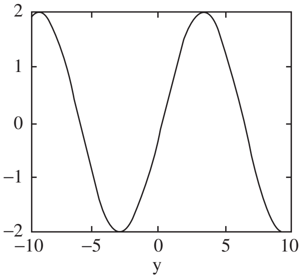
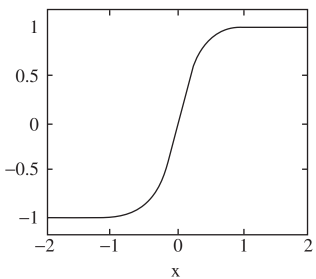
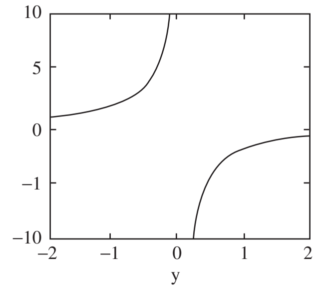
$$\sqrt{1-y^2}$$

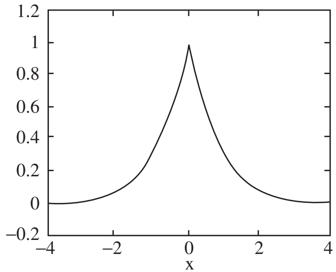
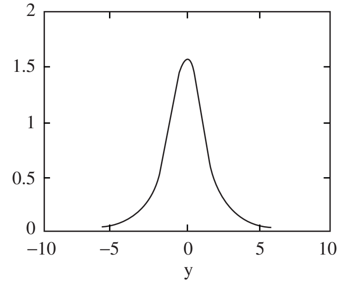
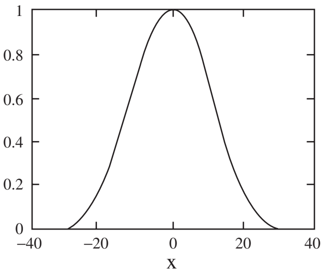
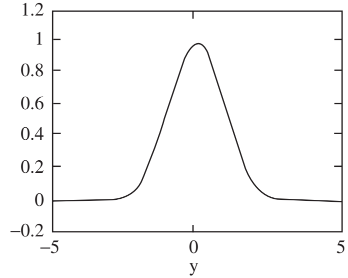
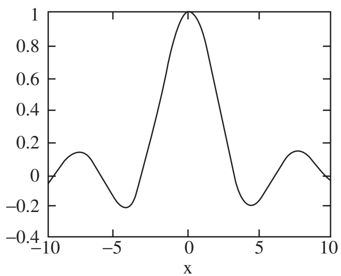
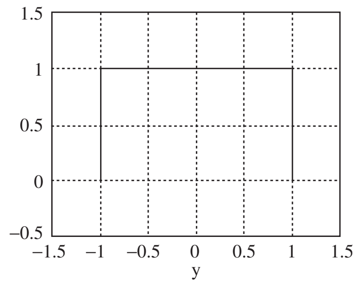


$$\frac{1}{\pi x}$$



$$\text{sqn } y = \begin{cases} 1 & y > 0 \\ 0 & y = 0 \\ -1 & y < 0 \end{cases}$$

$f(x)$	$F(y)$
 $xe^{-\pi x^2}$	 $-j\frac{y}{2\pi}e^{-\frac{y^2}{4\pi}}$
 $\delta(x+a)-\delta(x-a)$	 $2j\sin\frac{y}{2}$
 $\tanh \pi x$	 $-j\,\mathrm{cosech}\,\frac{y}{2}$

$f(x)$	$F(y)$
 $e^{-\lvert x\rvert}\dfrac{\sin x}{x}$	 $\tan^{-1}\dfrac{2}{y^2}$
 $p(x)*p(x)*p(x)$	 $\left(\dfrac{\sin y}{y}\right)^3$
 $\dfrac{\sin ax}{\pi x}$	 $P_a(x)$

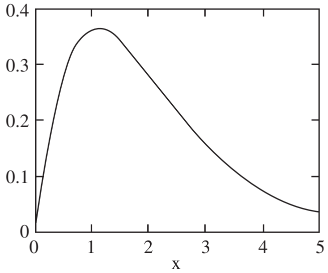
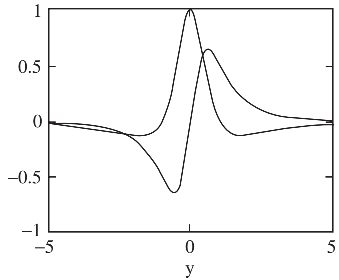
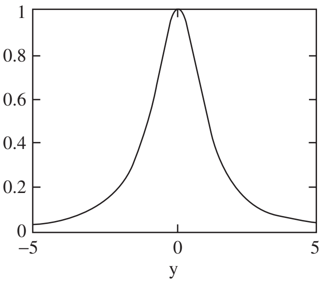
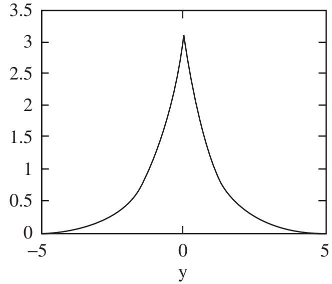
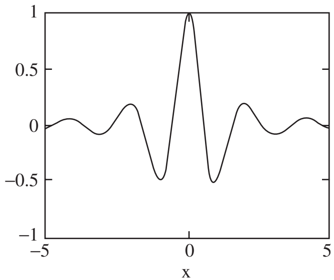
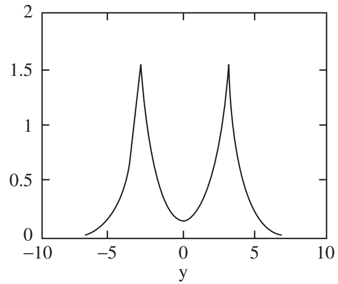
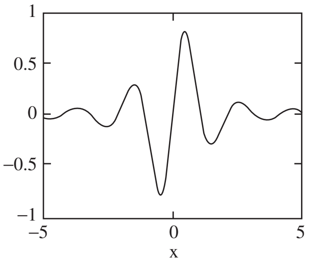
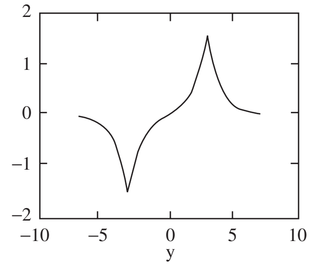
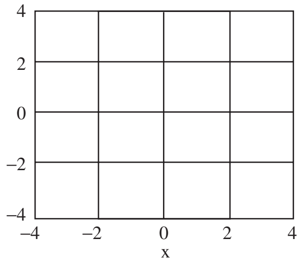
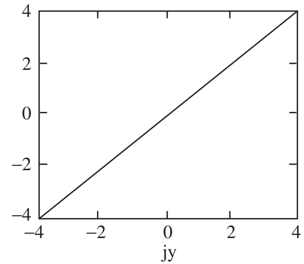
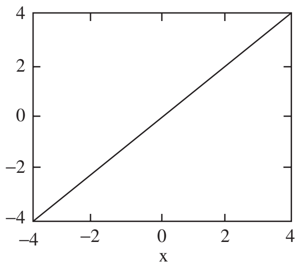
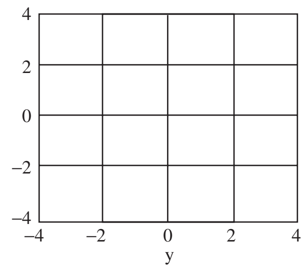
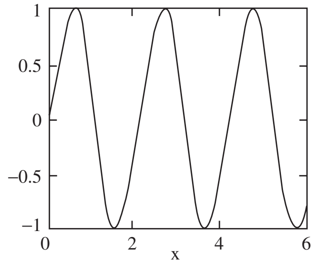
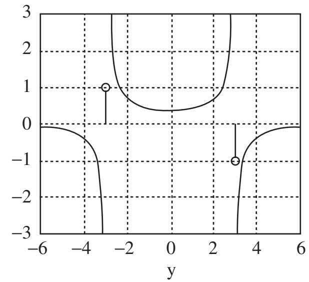
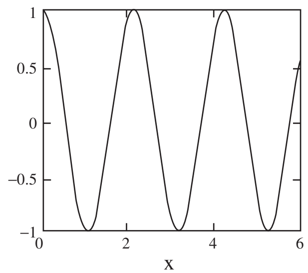
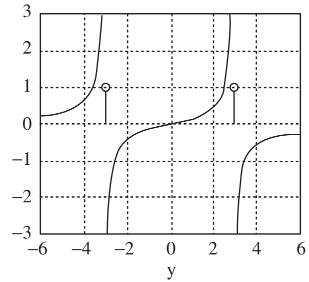
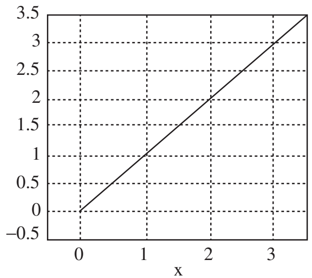
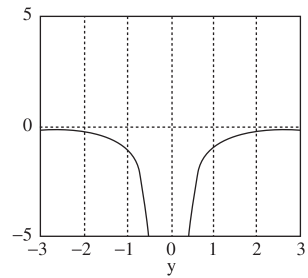
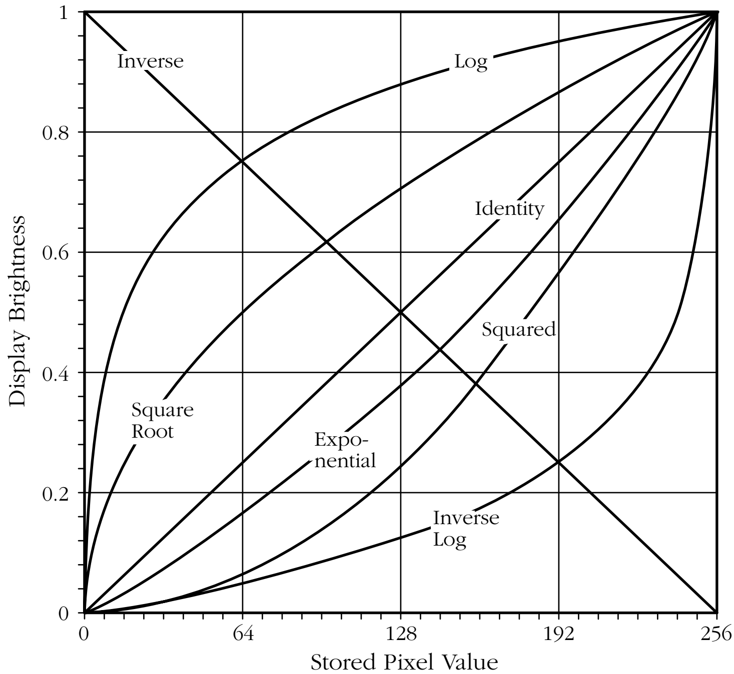
$f(x)$	$F(y)$
 $x\,e^{-ax}$ $\quad a>0 \quad x \geq 0$	 $\dfrac{a^2 - y^2}{\left(a^2 + y^2\right)^2} - j\,\dfrac{2ay}{\left(a^2 + y^2\right)^2}$
 $\dfrac{1}{a^2 + x^2}$	 $\dfrac{\pi}{a}\,d^{-a\lvert y \rvert}$
 $\dfrac{\cos bx}{a^2 + x^2}$	 $\dfrac{\pi}{2a}\left[e^{-a\lvert y-b \rvert} + e^{-a\lvert y+b \rvert}\right]$

Table of Fourier Transforms ($x = t$, $y = w$) (continued)

$f(x)$		$F(y)$	
	$\frac{\sin bx}{a^2 + x^2}$		$\frac{\pi}{2aj}\left[e^{-a\|y-b\|} - e^{-a\|y+b\|}\right]$
	$\frac{d\delta(x)}{dx}$		jy
			$2\pi j \frac{d\delta(y)}{dy}$

$f(x)$		$F(y)$	
	$\sin w_0 x \quad x \geq 0$ $0 \quad x < 0$		$\frac{w_0}{w_0^2 - y^2} - j\frac{\pi}{2}\left[\delta(y - w_0) - \delta(y + w_0)\right]$
	$\cos w_0 x \quad x \geq 0$ $0 \quad x < 0$		$\frac{jy}{w_0^2 - y^2} + \frac{\pi}{2}\left[\delta(y - w_0) - \delta(y + w_0)\right]$
	$x \quad x \geq 0$ $0 \quad x < 0$		$j\pi \frac{d\delta(y)}{dy} - \frac{1}{y^2}$

From Poularikas, A., Fourier transformation, in *The Handbook of Formulas and Tables for Signal Processing*, CRC Press, Boca Raton, FL, 1999, pp. **3**-4 to **3**-27.



Examples of display transfer functions. (From Russ, J.C., Image enhancement: Processing in the spatial domain, in *The Image Processing Handbook,* 3rd ed., CRC Press, Boca Raton, FL, 1999, p. 232.)

Common Fourier Transforms

$x(t)$	$X(j\omega)$
$\delta(t)$	1
1	$2\pi\delta(\omega)$
$u(t)$	$\pi\delta(\omega)+\frac{1}{j\omega}$
$e^{-at}u(t),\ a>0$	$\frac{1}{a+j\omega}$
$te^{-at}u(t),\ a>0$	$\frac{1}{(a+j\omega)^2}$
$\sin(\omega_o t)$	$j\pi[\delta(\omega+\omega_o)-\delta(\omega-\omega_o)]$
$\cos(\omega_o t)$	$\pi[\delta(\omega+\omega_o)+\delta(\omega-\omega_o)]$

From Heinen, J.A. and Niederjohn, R.J., Signal processing, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 77.

Common Laplace Transforms

$x(t)$	$X(s)$
$d(t)$	1
$u(t)$	$\frac{1}{s}, \text{Re}\{s\} > 0$
$e^{-at}u(t)$	$\frac{1}{s+a}, \text{Re}\{s\} > -a$
$te^{-at}u(t)$	$\frac{1}{(s+a)^2}, \text{Re}\{s\} > -a$
$\sin(\omega_o t)u(t)$	$\frac{\omega_o}{s^2+\omega_o^2}, \text{Re}\{s\} > 0$
$\cos(\omega_o t)u(t)$	$\frac{s}{s^2+\omega_o^2}, \text{Re}\{s\} > 0$

From Heinen, J.A. and Niederjohn, R.J., Signal processing, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 78.

Important Properties of Laplace Transforms

Signals	Laplace Transforms
$Ax_1(t) + Bx_2(t)$	$AX_1(s) + BX_2(s)$
$x(t - t_o),\ t_o \geq 0$	$X(s)e^{-st_o}$
$x(at),\ a > 0$	$\frac{1}{a}X\left(\frac{s}{a}\right)$
$\frac{dx(t)}{dt}$	$sX(s) - x(0-)$
$\int_{-\infty}^{t} x(\tau)d\tau$	$\frac{X(s)}{s}$
$x_1(t)^* x_2(t)$	$X_1(s)X_2(s)$

Note: $x(t)$, $x_1(t)$, $x_2(t)$ are arbitrary signals with Laplace transforms $X(s)$, $X_1(s)$, $X_2(s)$, respectively. A, B, a, t_o are arbitrary constants.

From Heinen, J.A. and Niederjohn, R.J., Signal processing, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 79.

Representative Values of Absolute Seebeck Thermoelectric Coefficients of Some Materials Used in Industrial Electronic Circuits

	Seebeck Coefficient, µV/°C			
	0°C	20°C	100°C	400°C
Lead	0.03×10^{-3}	0.05×10^{-3}	0.08×10^{-3}	0.11×10^{-3}
Tin	0.03×10^{-3}	0.06×10^{-3}	0.09×10^{-3}	0.12×10^{-3}
Copper	1.72	1.82	2.23	3.85
Silver	1.42	1.50	1.84	4.07
Gold	2.3	2.12	2.0	2.3
Tungsten	1.9	4.1	6.7	12.1
Chromium	13.2	14.4	15.3	17.3
Nickel	–7.0	–9.7	–12.4	–15.0
Platinum	–4.2	–7.2	–9.7	–13.1
Brass	0.7	0.82	1.33	1.95
Kovar	0.20	0.20	0.19	0.02
Manganin	1.37	1.39	1.45	1.95
Nichrome	20.84	20.24	17.85	11.89
Silicon	–408	417	–455	–502
Germanium	–303			
CuO	–696			
Cu_2O	–474 – 1150			
Mn_2O_3	–385			

Note: Values reported in the literature are for nominal materials that may not be well documented as to composition and state. They are presented only to allow estimates of plausible Seebeck emf contributions. Specific values should be determined for critical applications.

From Reed, R.P., Measurement system architecture — Thermal effects in industrial electronic circuits, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 153.

Data originally from Reed, R.P. 1992. Absolute Seebeck thermoelectric characteristics—principles, significance, and applications, *Temperature, Its Measurement and Control in Science and Industry*, American Institute of Physics, 6(2):503–508.

Reed, R.P. 1993. *Manual on the Use of Thermocouples in Temperature Measurement, MNL-12, 4th edition*, Ch. 2, Park, R.W., ed., American Society for Testing and Materials, Philadelphia, PA.

Wang, T.P. 1992. Absolute Seebeck coefficients of metallic elements, *Temperature, Its Measurement and Control in Science and Industry*, American Institute of Physics, 6(2):509–514.

Kinzie, P.A. 1973. *Thermocouple Temperature Measurement*, Wiley-Interscience.

Power Definitions (Single-Phase Circuits)

Quantity (and Synonyms)	Symbol	Relationships	Units
Active power (real power, average power)	P	$P = \lvert V_{rms}\rvert \lvert I_{rms}\rvert \cos(\phi) = \lvert V_{rms}\rvert \lvert I_{rms}\rvert pf = \sqrt{S^2 - Q^2}$	Watt (W)
Reactive power	Q	$Q = \lvert V_{rms}\rvert \lvert I_{rms}\rvert \sin(\phi) = \lvert V_{rms}\rvert \lvert I_{rms}\rvert rpf = \sqrt{S^2 - P^2}$	VAr
Power factor	pf	$\cos(\phi)$	None, often represented as a percentage
Reactive power factor	rpf	$\sin(\phi)$	None
Complex power	S	$S = VI^*$	Voltamperes (VA)
Apparent power	|S|	$\lvert S\rvert = \lvert V_{rms}\rvert \lvert I_{rms}\rvert = \sqrt{P^2 + Q^2}$	Voltamperes (VA)

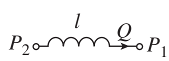
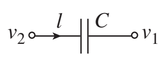
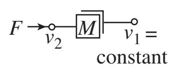
From Heydt, G., Main disturbances — Reactive power and harmonics compensation, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 357.

Power Definitions (Three-Phase Circuits)

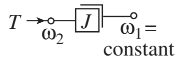
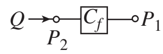
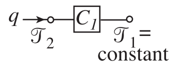
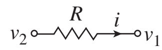
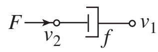
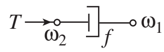
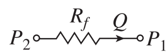
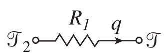
Quantity	Symbol	Relationships	Units
Active power (real power)	P	$P = 3\lvert V_{ln}\rvert\lvert I_{phase}\rvert\cos(\phi)$	Watt (W)
		$= 3\lvert V_{ln}\rvert\lvert I_{phase}\rvert pf$	
		$= \sqrt{3}\lvert V_{ll}\rvert\lvert I_{line}\rvert pf$	
		$= \sqrt{S^2 - Q^2}$	
Reactive power	Q	$Q = 3\lvert V_{ln}\rvert\lvert I_{phase}\rvert\sin(\phi)$	VAr
		$= 3\lvert Vrubln\rvert\lvert I_{phase}\rvert rpf$	
		$= \sqrt{3}\lvert V_{ll}\rvert\lvert I_{line}\rvert rpf$	
		$= \sqrt{S^2 - p^2}$	
Power factor	pf	$\cos(\phi)$	Often represented as a percentage
Reactive power factor	rpf	$\sin(\phi)$	None
Complex power	S	$S = 3V_{\ln}I^*_{phase}$	Voltamperes (VA)
		$= \sqrt{3} - 30°V_{line}I^*_{line}$	
Apparent power	|S|	$\lvert S\rvert = 3\lvert V_{\ln}\rvert\lvert I_{phase}\rvert$	Voltamperes (VA)
		$= 3\lvert V_{ll}\rvert\lvert I_{line}\rvert$	
		$= \sqrt{P^2 + Q^2}$	

From Heydt, G., Main disturbances — Reactive power and harmonics compensation, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 357.

Summary of Describing Differential Equations for Ideal Elements

Type of Element	Physical Elements	Describing Equation	Energy E or Power P	Symbol
	Electrical inductance	$v_{21} = L\frac{di}{dt}$	$E = \frac{1}{2}Li^2$	
Inductive storage	Translational spring	$v_{21} = \frac{1}{K}\frac{dF}{dt}$	$E = \frac{1}{2}\frac{F^2}{K}$	
	Rotational spring	$\omega_{21} = \frac{1}{K}\frac{dT}{dt}$	$E = \frac{1}{2}\frac{T^2}{K}$	
	Fluid inertia	$P_{21} = I\frac{dQ}{dt}$	$E = \frac{1}{2}IQ^2$	
	Electrical capacitance	$i = C\frac{dv_{21}}{dt}$	$E = \frac{1}{2}Cv_{21}^2$	
	Translational mass	$F = M\frac{dv_2}{dt}$	$E = \frac{1}{2}Mv_2^2$	

Summary of Describing Differential Equations for Ideal Elements (continued)

Type of Element	Physical Elements	Describing Equation	Energy E or Power P	Symbol
Capacitive storage	Rotational mass	$T = J\dfrac{d\omega_2}{dt}$	$E = \dfrac{1}{2}J\omega_2^2$	
	Fluid capacitance	$Q = C_f\dfrac{dP_{21}}{dt}$	$E = \dfrac{1}{2}C_f P_{21}^2$	
	Thermal capacitance	$q = C_t\dfrac{d\tau_2}{dt}$	$E = C_t\tau_2$	
	Electrical resistance	$i = \dfrac{1}{R}v_{21}$	$P = \dfrac{1}{R}v_{21}^2$	
	Translational damper	$F = fv_{21}$	$P = fv_{21}^2$	
Energy dissipators	Rotational damper	$T = f\omega_{21}$	$P = f\omega_{21}^2$	
	Fluid resistance	$Q = \dfrac{1}{R_f}P_{21}$	$P = \dfrac{1}{R_f}P_{21}^2$	
	Thermal resistance	$q = \dfrac{1}{R_t}T_{21}$	$P = \dfrac{1}{R_t}T_{21}$	

Nomenclature

- *Through-variable*: F = force, T = torque, i = current, Q = fluid volumetric flow rate, q = heat flow rate.
- *Across-variable*: v = translational velocity, ω = angular velocity, v = voltage, P = pressure, T = temperature.
- *Inductive storage*: L = inductance, $1/k$ = reciprocal translational or rotational stiffness, I = fluid inertance.
- *Capacitive storage*: C = capacitance, M = mass, J = moment of inertia, C_f = fluid capacitance, C_t = thermal capacitance.
- *Energy dissipators*: R = resistance, f = viscous friction, R_f = fluid resistance, R_t = thermal resistance.

From Boye, A.J. and Brogan, W.L., Modeling for system control, in *The Industrial Electronics Handbook*, Irwin, J.O., Ed., CRC Press, Boca Raton, FL, 1997, p. 449. Originally from Dorf, R. and Bishop, R. 1995. *Modern Control Systems,* 7th ed. © 1995 by Addison-Wesley Publishing Company. Reprinted by permission.

Properties of the Wave Types for Time-of-Flight Measuring

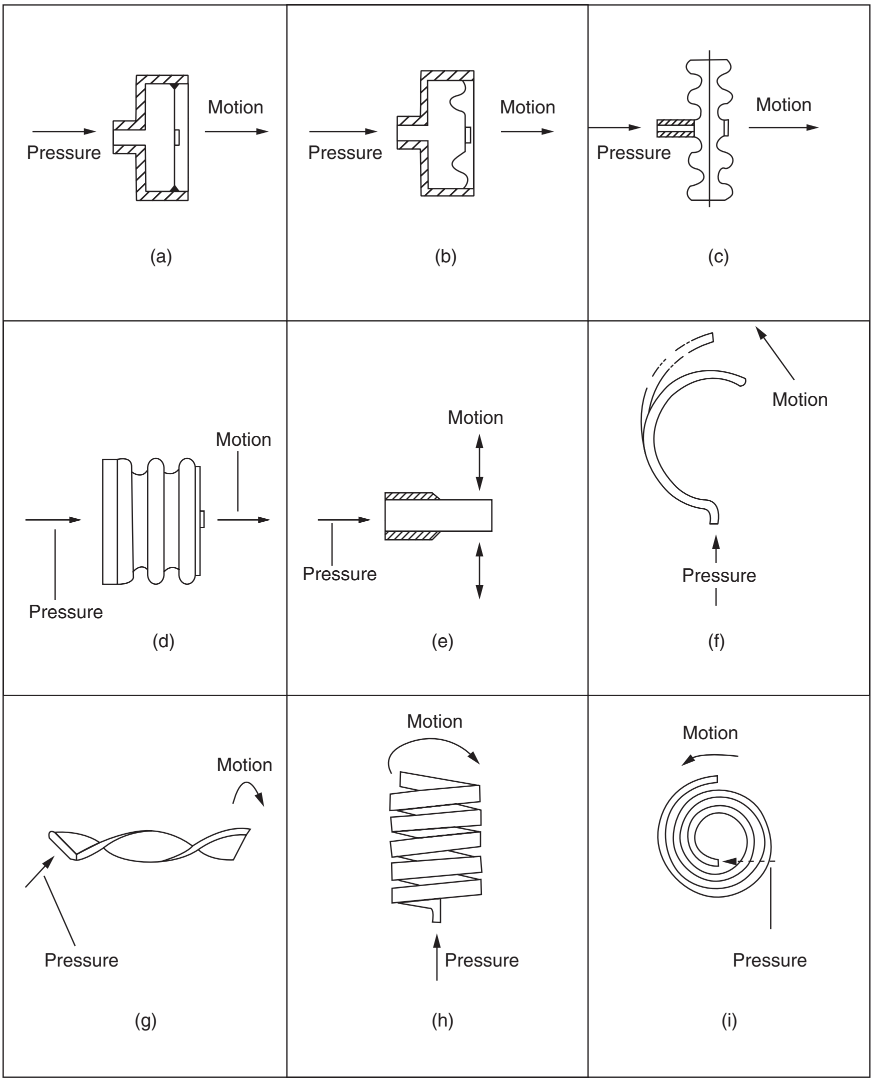
Principle	Wave Velocity	Avg. Carrier Frequency	Wavelength	Avg. Burst Time
Ultrasonic	340 m s^{-1}	50 kHz	7 mm	1 ms
Radar	300,000 km s^{-1}	10 GHz	3 cm	1 ns
Laser	300,000 km s^{-1}	300 THz	1 μm	1 ns

From Brumbi, D., Level measurement, in *The Measurement, Instrumentation and Sensors Handbook,* Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **11**-8.

Comparison of Strain Sensors

Description	Longitudinal strain sensitivity	Transverse strain sensitivity	Temperature sensitivity	Strain resolution	Spatial resolution	Time resolution	Measurable strain range
Piezoresistive constantan foil	$\Delta R/R/\Delta\varepsilon_L = 2.1$	$\Delta R/R/\Delta\varepsilon_t = <0.02$	$\Delta R/R/\Delta T = 2 \times 10^{-6}/°C$	<1 μstrain[a]	5–100 mm[b]	<1 μs[c]	0–3%
Annealed constantan foil[d]	$\Delta R/R/\Delta\varepsilon_L = 2.1$	$\Delta R/R/\Delta\varepsilon_t = <0.02$	$\Delta R/R/\Delta T = 2 \times 10^{-6}/°C$	<11 μstrain	5–100 mm	<1 μs	0–10%
Piezoresistive semiconductor	$\Delta R/R/\Delta\varepsilon_L = 150$	$\Delta R/R/\Delta\varepsilon_t =$???	$\Delta R/R/\Delta T = 1.7 \times 10^{-3}/°C$	<0.1 μstrain	1–15 mm	<1 μs	0–0.1%
Piezoelectric PVDF	$\Delta Q/A/\Delta\varepsilon_L = 120$ nC/m²/με	$\Delta Q/A/\Delta\varepsilon_t = 60$ nC/m²/με	$\Delta Q/A/\Delta T = -27$ μC/m²/°C	1–10 μstrain	Gage size	<1 μs	0–30%
Piezoelectric quartz	$\Delta Q/A/\Delta\varepsilon_L = 150$ nC/m²/με bonded to steel		$\Delta Q/A/\Delta T = 0$	<0.01 μstrain 20 mm gage	Gage size	<10 μs	0–0.1%
Fiber optic Fabry-Perot	2 to 1000 μstrain/volt	Near zero		<1 μstrain	2–10 mm	<20 μs	
Birefringent Film	$K^e = 0.15–0.002$				0.5 mm[f]	<5 μs	0.05–5%
Moiré	1 fringe order/417 nm displ.	1 fringe order/417 nm displ.	Not defined	41.7 με over 10 mm	full field[g]	Limited by signal conditining	0.005–5%

[a] With good signal conditioning.
[b] Equal to grid area.
[c] Gage response is within 100 ns. Most signal conditioning limits response time to far less than this.
[d] Annealed foil has a low yield stress and a large strain to failure. It also has hysteresis in the unload and a zero shift under cyclic load.
[e] This technique measures a difference in principal strains. $\varepsilon_2 - \varepsilon_1 = N\lambda/2tK$
[f] Approximately the film thickness.
[g] The spatial strain resolution depends on the strain level. This is a displacement measurement technique.
From Lynch, C.S., Strain measurement, in *The Measurement, Instrumentation, and Sensors Handbook,* Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **22**-5.

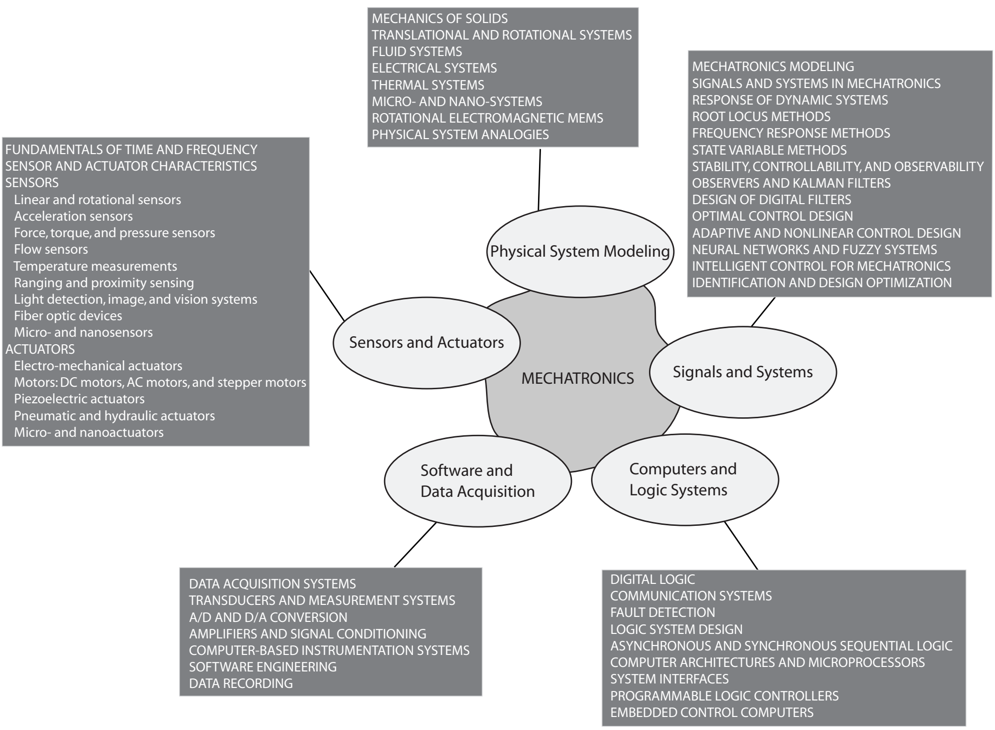


Pressure-sensing elements: (a) flat diaphragm; (b) corrugated diaphragm; (c) capsule; (d) bellows; (e) straight tube; (f) Cshaped Bourdon tube; (g) twisted Bourdon tube; (h) helical Bourdon tube; (i) spiral Bourdon tube. (From Norton, H.N., *Handbook of Transducers,* Englewood Cliffs, NJ: Prentice-Hall, 1989, 294–330. Reprinted with permission.) Previously published in Chau, K.H.L., Pressure and sound measurement, in *The Measurement, Instrumentation, and Sensors Handbook,* Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **26**-3.)

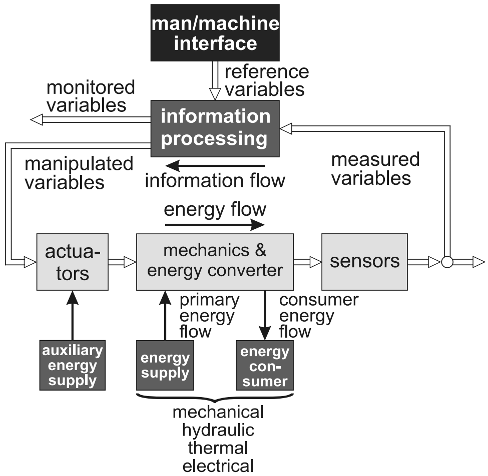
Permittivity (Dielectric Constants of Materials Used in Capacitors)

Material	Permittivity
Vacuum	1.0
Air	1.0006
Teflon	2.1
Polyethylene, etc.	2.0–3.0
Impregnated paper	4.0–6.0
Glass and mica	4.0–7.0
Ceramic (low *K*)	≤20.0
Ceramic (medium *K*)	80.0–100.0
Ceramic (high *K*)	≥1000,0

From Eren, H. and Goh, J., Capacitance and capacitance measurements, in *The Measurement, Instrumentation, and Sensors Handbook*, Webster, J.G., Ed., CRC Press, Boca Raton, FL, 1999, p. **45**-5.



The key elements of mechatronics. (From Bishop, R.H., What is mechatronics? in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-3.)



Mechanical process and information processing develop towards mechatronic systems. (From Iserman, R., Mechatronic design approach, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **2**-3.)

Generalized Through and Across Variables for Processes with Energy Flow

System	Through Variables		Across Variables	
Electrical	Electric current	I	Electric voltage	U
Magnetic	Magnetic Flow	Φ	Magnetic force	Θ
Mechanical				
• translation	Force	F	Velocity	w
• rotation	Torque	M	Rotational speed	ω
Hydraulic	Volume flow	$\dot{V}$	Pressure	p
Thermodynamic	Entropy flow		Temperature	T

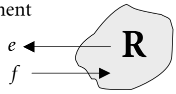
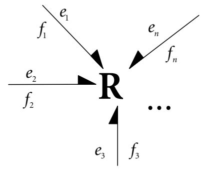
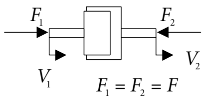
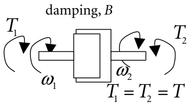
From Iserman, R., Mechatronic design approach, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **2**-12.

Power and Energy Variables for Mechanical Systems

Energy Domain	Effort, e	Flow, f	Power, P
General	e	f	$e \cdot f$ [W]
Translational	Force, F [N]	Velocity, V [m/sec]	$F \cdot V$ [N m/sec, W]
Rotational	Torque, T or τ [N m]	Angular velocity, ω [rad/sec]	$T \cdot \omega$ [N m/sec, W]
Electrical	Voltage, v [V]	Current, i [A]	$v \cdot i$ [W]
Hydraulic	Pressure, P [Pa]	Volumetric flowrate, Q [m^3/sec]	$P \cdot Q$ [W]

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-3.

Mechanical Dissipative Elements

Physical System	Fundamental Relations	Bond Graph
Generalized Dissipative Element  • Resistive element • **Resistance,** *R*	Dissipation: $\mathbf{e}\cdot\mathbf{f} = \sum_i e_i f_i = T \cdot f_s$ Resistive law: $e = \Phi_R(f)$ Conductive law: $f = \Phi_R^{-1}(e)$ Content: $P_f = \int e \cdot df$ Co-content: $P_e = \int f \cdot de$	 **Generalized multiport R-element**
Mechanical Translation  $F_1 = F_2 = F$ • Damper $V_1 - V_2 = V$ • **damping,** *b*	Constitutive: $F = \Phi(V)$ Content: $P_V = \int F \cdot dV$ Co-energy: $P_F = \int V \cdot dF$ Dissipation: $P_d = P_V + P_F$	$\xrightarrow[V]{F}$ **R**:*b* Linear: $F = b \cdot V$ Dissipation: $P_d = bV^2$
Mechanical Rotation  $T_1 = T_2 = T$ $\omega_1 - \omega_2 = \omega$ • Torsional damper • **damping,** *B*	Constitutive: $T = \Phi(\omega)$ Content: $P_\omega = \int T \cdot d\omega$ Co-energy: $P_T = \int \omega \cdot dT$ Dissipation: $P_d = P_\omega + P_T$	$\xrightarrow[\omega]{T}$ **R**:*B* Linear: $T = B \cdot \omega$ Dissipation: $P_d = B\omega^2$

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-11.

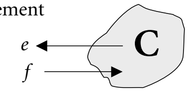
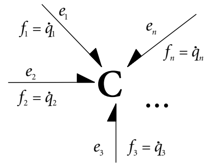
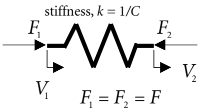
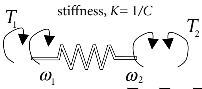
Typical Coefficient of Friction Values

Contacting Surfaces	Static, μ_s	Sliding or Kinetic, μ_k
Steel on steel (dry)	0.6	0.4
Steel on steel (greasy)	0.1	0.05
Teflon on steel	0.04	0.04
Teflon on teflon	0.04	—
Brass on steel (dry)	0.5	0.4
Brake lining on cast iron	0.4	0.3
Rubber on asphalt	—	0.5
Rubber on concrete	—	0.6
Rubber tires on smooth pavement (dry)	0.9	0.8
Wire rope on iron pulley (dry)	0.2	0.15
Hemp rope on metal	0.3	0.2
Metal on ice	—	0.02

Note: Actual values will vary significantly depending on conditions.

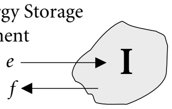
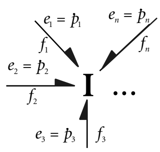
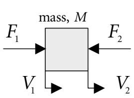
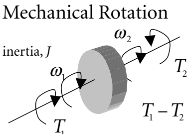
From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-11.

Mechanical Potential Energy Storage Elements (Integral Form)

Physical System	Fundamental Relations	Bond Graph
Generalized Potential Energy Storage Element  • Capacitive element • **Capacitance,** C	State: $\mathbf{q} = \text{displacement}$ Rate: $\dot{\mathbf{q}} = \mathbf{f}$ Constitutive: $\mathbf{e} = \Phi(\mathbf{q})$ Energy: $U_{\mathbf{q}} = \int \mathbf{e} \cdot d\mathbf{q}$ Co-energy: $U_{\mathbf{e}} = \int \mathbf{q} \cdot d\mathbf{e}$	 **Generalized multiport C-element**
Mechanical Translation  $F_1 = F_2 = F$ • spring $V_1 - V_2 = V$ • **stiffness,** k, **compliance,** C	State: $x = \text{displacement}$ Rate: $\dot{x} = V$ Constitutive: $F = F(x)$ Energy: $U_x = \int F \cdot dx$ Co-energy: $U_F = \int x \cdot dF$	$\xrightarrow[\dot{x}=V]{F}$ $\mathbf{C}{:}\,1/C = k$ Linear: $F = k \cdot x$ Energy: $U_x = \frac{1}{2}kx^2$ Co-energy: $U_F = F^2 / 2k$
Mechanical Rotation  $T_1 = T_2 = T$ $\omega_1 - \omega_2 = \omega$ • Torsional spring • **stiffness,** K, **compliance,** C	State: $\theta = \text{angle}$ Rate: $\dot{\theta} = \omega$ Constitutive: $T = T(\theta)$ Energy: $U_\theta = \int T \cdot d\theta$ Co-energy: $U_T = \int \theta \cdot dT$	$\xrightarrow[\dot{\theta}=\omega]{T}$ $\mathbf{C}{:}\,1/C = K$ Linear: $T = K \cdot \theta$ Energy: $U_\theta = \frac{1}{2}k\theta^2$ Co-energy: $U_T = T^2 / 2K$

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook*, Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-13.

Mechanical Kinetic Energy Storage Elements (Integral Form)

Physical System	Fundamental Relations	Bond Graph
Generalized Kinetic Energy Storage Element  • Inertive element • **Inertance,** I	State: $\mathbf{p} = \text{momentum}$ Rate: $\dot{\mathbf{p}} = \mathbf{e}$ Constitutive: $\mathbf{f} = \Phi(\mathbf{p})$ Energy: $T_{\mathbf{p}} = \int \mathbf{f} \cdot d\mathbf{p}$ Co-energy: $T_{\mathbf{f}} = \int \mathbf{p} \cdot d\mathbf{f}$	 **Generalized multiport I-element**
Mechanical Translation  $F_1 - F_2 = F$ • Mass $V_1 = V_2 = V$ • **mass,** m	State: $p = \text{momentum}$ Rate: $\dot{p} = F$ Constitutive: $V = V(p)$ Energy: $T_p = \int f \cdot dp$ Co-energy: $T_V = \int p \cdot dV$	$\xrightarrow[V]{\dot{p}=F}$ $\mathbf{I}{:}M$ Linear: $V = p / M$ Energy: $T_p = p^2 / 2M$ Co-energy: $T_V = \frac{1}{2}MV^2$
Mechanical Rotation  $T_1 - T_2 = T$ $\omega_1 = \omega_2 = \omega$ • Rotational inertia • **mass moment of inertia,** J	State: $h = \text{angular momentum}$ Rate: $\dot{h} = T$ Constitutive: $\omega = \omega(h)$ Energy: $T_h = \int \omega \cdot dh$ Co-energy: $T_\omega = \int h \cdot d\omega$	$\xrightarrow[\omega]{\dot{h}=T}$ $\mathbf{I}{:}J$ Linear: $\omega = h / J$ Energy: $T_h = h^2 / 2J$ Co-energy: $T_\omega = \frac{1}{2}J\omega^2$

From Longoria, R.G., Modeling of mechanical systems for mechatronics applications, in *The Mechantronics Handbook*, Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **9**-14.

Resistance of Copper Wire

AWG Size	Number of Strands	Diameter per Strand	Resistance per 1000 ft (Ω)
24	Solid	0.0201	28.4
24	7	0.0080	28.4
22	Solid	0.0254	18.0
22	7	0.0100	19.0
20	Solid	0.0320	11.3
20	7	0.0126	11.9
18	Solid	0.0403	7.2
18	7	0.0159	7.5
16	Solid	0.0508	4.5
16	19	0.0113	4.7

From Rizzoni, G., Electrical engineering, in *The Mechatronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, p. **11**-9.

Type of Sensors for Various Measurement Objectives

Sensor	Features
	Linear/Rotational sensors
Linear/Rotational variable differential transducer (LVDT/RVDT)	High resolution with wide range capability Very stable in static and quasi-static applications
Optical encoder	Simple, reliable, and low-cost solution Good for both absolute and incremental measurements
Electrical tachometer	Resolution depends on type such as generator or magnetic pickups
Hall effect sensor	High accuracy over a small to medium range
Capacitive transducer	Very high resolution with high sensitivity Low power requirements Good for high frequency dynamic measurements
Strain gauge elements	Very high accuracy in small ranges Provides high resolution at low noise levels
Interferometer	Laser systems provide extremely high resolution in large ranges Very reliable and expensive
Magnetic pickup	Output is sinusoidal
Gyroscope	
Inductosyn	Very high resolution over small ranges
	Acceleration sensors
Seismic accelerometer	Good for measuring frequencies up to 40% of its natural frequency
Piezoelectric accelerometer	High sensitivity, compact, and rugged Very high natural frequency (100 kHz typical)
	Force, torque, and pressure sensors
Strain gauge	Good for both static and dynamic measurements
Dynamometers/load cells	They are also available as micro- and nanosensors
Piezoelectric load cells	Good for high precision dynamic force measurements
Tactile sensor	Compact, has wide dynamic range, and high
Ultrasonic stress sensor	Good for small force measurements
	Flow sensors
Pitot tube	Widely used as a flow rate sensor to determine speed in aircrafts
Orifice plate	Least expensive with limited range
Flow nozzle, venturi tubes	Accurate on wide range of flow More complex and expensive

Type of Sensors for Various Measurement Objectives (continued)

Sensor	Features
Rotameter	Good for upstream flow measurements
	Used in conjunction with variable inductance sensor
Ultrasonic type	Good for very high flow rates
	Can be used for both upstream and downstream flow measurements
Turbine flow meter	Not suited for fluids containing abrasive particles
	Relationship between flow rate and angular velocity is linear
Electromagnetic flow meter	Least intrusive as it is noncontact type
	Can be used with fluids that are corrosive, contaminated, etc.
	The fluid has to be electrically conductive
	Temperature sensors
Thermocouples	This is the cheapest and the most versatile sensor
	Applicable over wide temperature ranges (−200°C to 1200°C typical)
Thermistors	Very high sensitivity in medium ranges (up to 100°C typical)
	Compact but nonlinear in nature
Thermodiodes, thermo transistors	Ideally suited for chip temperature measurements
	Minimized self-heating
RTD—resistance temperature detector	More stable over a long period of time compared to thermocouple
	Linear over a wide range
Infrared type	Noncontact point sensor with resolution limited by wavelength
Infrared thermography	Measures whole-field temperature distribution
	Proximity sensors
Inductance, eddy current, hall effect, photoelectric, capacitance, etc.	Robust noncontact switching action
	The digital outputs are often directly fed to the digital controller
	Light sensors
Photoresistors, photodiodes, photo transistors, photo conductors, etc.	Measure light intensity with high sensitivity
	Inexpensive, reliable, and noncontact sensor
Charge-coupled diode	Captures digital image of a field of vision
	Smart material sensors
Optical fiber	
As strain sensor	Alternate to strain gages with very high accuracy and bandwidth
	Sensitive to the reflecting surface's orientation and status
As level sensor	Reliable and accurate
As force sensor	High resolution in wide ranges
As temperature sensor	High resolution and range (up to 2000°C)
Piezoelectric	
As strain sensor	Distributed sensing with high resolution and bandwidth
As force sensor	Most suitable for dynamic applications
As accelerometer	Least hysteresis and good setpoint accuracy
Magnetostrictive	
As force sensors	Compact force sensor with high resolution and bandwidth
	Good for distributed and noncontact sensing applications
As torque sensor	Accurate, high bandwidth, and noncontact sensor
	Micro- and nanosensors
Micro CCD image sensor	Small size, full field image sensor
Fiberscope	Small (0.2 mm diameter) field vision scope using SMA coil actuators
Micro-ultrasonic sensor	Detects flaws in small pipes
Micro-tactile sensor	Detects proximity between the end of catheter and blood vessels

From Anjanappa, M., Datta, K., and Song, T., Introduction to sensors and actuators, in *The Mechatronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, pp. **16**-2 to **16**-3.

Type of Actuators and Their Features

Actuator			Features
		Electrical	
Diodes, thyristor, bipolar transistor, triacs, diacs, power MOSFET, solid state relay, etc.			Electronic type Very high frequency response Low power consumption
		Electromechanical	
DC motor	Wound field	Separately excited	Speed can be controlled either by the voltage across the armature winding or by varying the field current
		Shunt	Constant-speed application
		Series	High starting torque, high acceleration torque, high speed with light load
		Compound	Low starting torque, good speed regulation Instability at heavy loads
	Permanent magnet	Conventional PM motor	High efficiency, high peak power, and fast response
		Moving-coil PM motor	Higher efficiency and lower inductance than conventional DC motor
		Torque motor	Designed to run for long periods in a stalled or a low rpm condition
	Electronic commutation (brushless motor)		Fast response High efficiency, often exceeding 75% Long life, high reliability, no maintenance needed Low radio frequency interference and noise production
AC motor	AC induction motor		The most commonly used motor in industry Simple, rugged, and inexpensive
	AC synchronous motor		Rotor rotates at synchronous speed Very high efficiency over a wide range of speeds and loads Need an additional system to start
	Universal motor		Can operate in DC or AC Very high horsepower per pound ratio Relatively short operating life
Stepper motor	Hybrid		Change electrical pulses into mechanical movement Provide accurate positioning without feedback
	Variable reluctance		Low maintenance
		Electromagnetic	
Solenoid type devices			Large force, short duration
Electromagnets, relay			On/off control
		Hydraulic and Pneumatic	
Cylinder			Suitable for liner movement
Hydraulic motor	Gear type		Wide speed range
	Vane type		High horsepower output
	Piston type		High degree of reliability
Air motor	Rotary type		No electric shock hazard
	Reciprocating		Low maintenance
Valves	Directional control valves		
	Pressure control valves		
	Process control valves		

Type of Actuators and Their Features (continued)

Actuator	Features
Smart Material actuators	
Piezoelectric & Electrostrictive	High frequency with small motion High voltage with low current excitation High resolution
Magnetostrictive	High frequency with small motion Low voltage with high current excitation
Shape Memory Alloy	Low voltage with high current excitation Low frequency with large motion
Electrorheological fluids	Very high voltage excitation Good resistance to mechanical shock and vibration Low frequency with large force
Micro- and Nanoactuators	
Micromotors	Suitable for micromechanical system
Microvalves	Can use available silicon processing technology, such as electrostatic motor
Micropumps	Can use any smart material

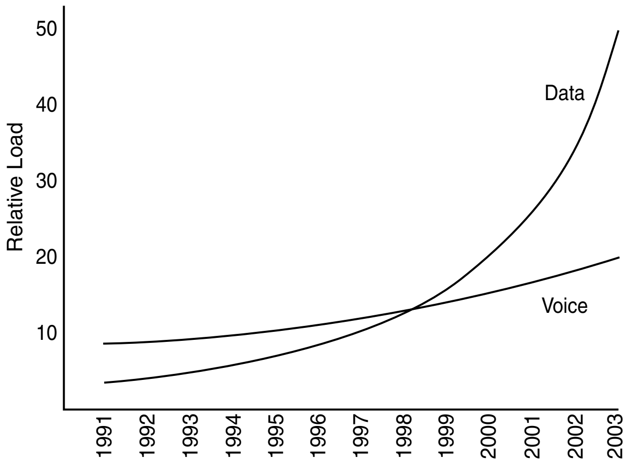
From Anjanappa, M., Datta, K., and Song, T., Introduction to sensors and actuators, in *The Mechatronics Handbook,* Bishop, R.H., Ed., CRC Press, Boca Raton, FL, 2002, pp. **16**-9 to **16**-10.

Performances of Two Deep-Sea Armored Coaxes

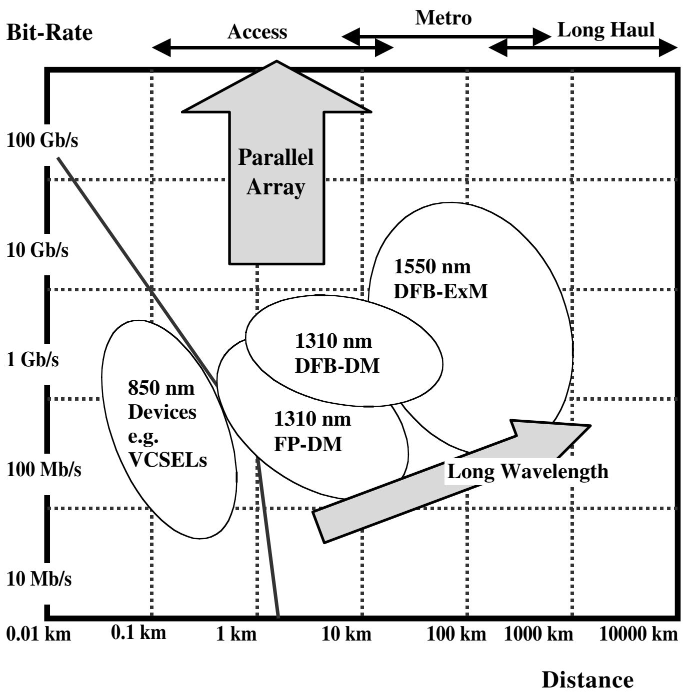
Cable Parameter	1972 Navy/SIO	1983 UNOLS
Diameter (mm)	17.3	17.3
Strength (kg)		
Ends fixed	17,000	17,800
One end free	11,900	17,300
Weight (kg/km)		
In air	1070	1020
In water	820	795
Free length (m)		
Ends fixed	20,800	22,300
One end free	14,500	21,800
Payload (kg)[a]		
Ends fixed	1880	2350
One end free	None	2150

[a]For operations to 6000 m, with the lower cable end free to rotate. The system's static strength/weight safety factor is 2.5.

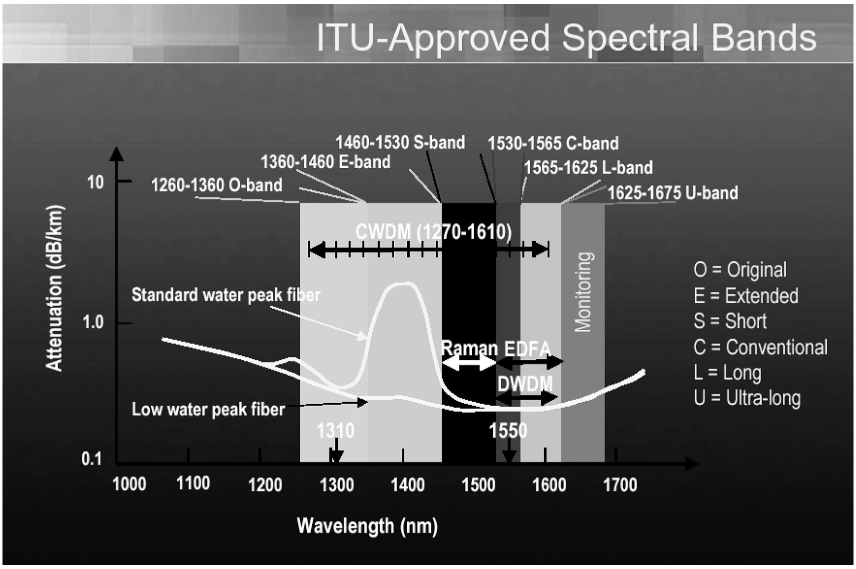
From Wilkins, G., Fiber optics telemetry in ocean cable systems, in *The Ocean Engineering Handbook,* El-Hawary, F., Ed., CRC Press, Boca Raton, FL, 2001, p. **5**-60.



Past and projected future growth of data and voice traffic. (From Gencata, A., Singhel, N., and Makherjee, B., Overview of optical communication networks, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 3.)



Nominal geographical spans of access, metro-core/regional, and long-haul networks as well as corresponding transmission rates with short- and long-wavelength transmitter devices. (From Raja, M.Y.A., Evolution of optical networks architecture, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 36.)



ITU-T-approved hand assignment in the low attenuation window of the silica fibers; the wavelength range involves 1260–1360 nm = O-band; 1360–1460 nm = E-band; 1460–1530 nm = S-band; 1530–1565 nm = C-band; 1565–1625 nm = L-band; and 1625–1675 nm = U-band (used in monitoring). (Courtesy EXFO Electro-Optical Engineering Inc. Printed with permission.) (From Raja, M.Y.A. and Ilyas, M., Optical transport networks: A physical layer perspective, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 391.)

Fiber Optics Chemical Sensors

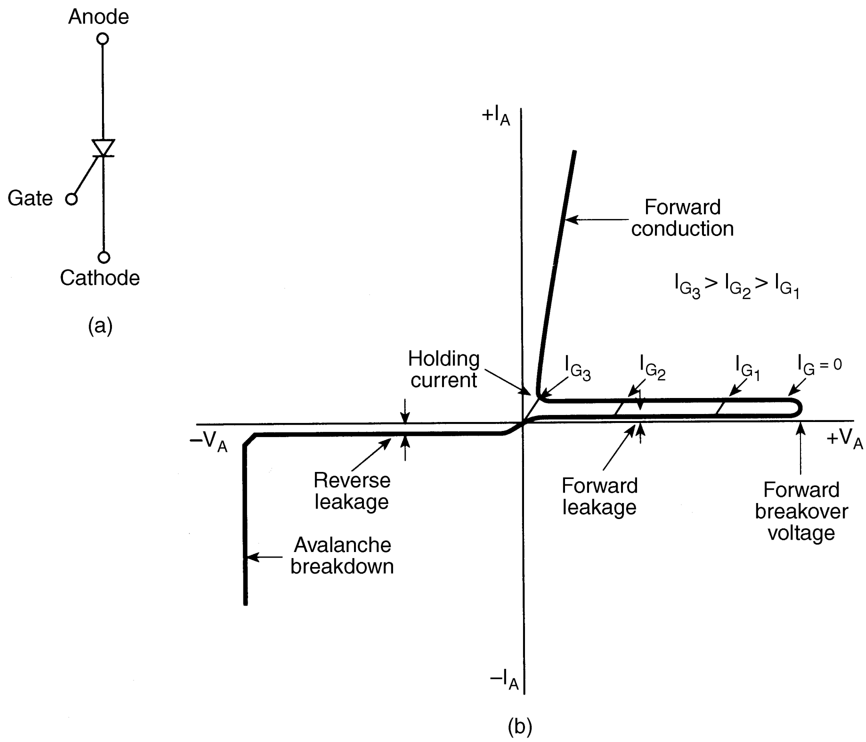
Sensor	Technique	Indicator	Principle	Wavelength (nm)			Detection limits	Sensitivity	Response Time	Ref.
				Excitation	Emission	Absorption				
Hydrogen sulphide	Porous fiber and sol-gel coating	Thionine	Florescence quenching	580	630	—	>50 ppb in H2S in water	~5 ppb	~5 S	57
pH	Porous fiber and sol-gel coating	Bromocresol green	Transmission/ absorption	—	615	—	3–6	~0.01 pH	~2 S	37
pH	Porous fiber and sol-gel coating	Bromocresol purple	Transmission/ absorption	—	—	580	6–9	~0.01 pH	~2 S	37
Hydrogen	Palladium coated fiber	Palladium thin films	Transmission/ absorption	—	—	650	0.2–0.6%	—	20–30 S	41
Carbon monoxide	Porous fiber	Organometallic complex in chloroform solution	Transmission/ absorption	—	—	450	9–28 vol.% in N_2 gas	~0.5 vol%	~100 S	27
Carbon dioxide dissolved in sea water	Fiber dipped in HPTS solution	Aqueous solution of 8-hydroxy-1,3,6-pyrenetrisulfonic acid-trisodium salt	Fluorescence	450	530	—	0–600 ppm	—	5 min	58
Oxygen dissolved oxygen	Porous fiber and sol-gel coating	Ruthenium complex	Fluorescence quenching	450	610	—	0–10% Oxygen 0.25–9 ppm dissolved oxygen	—	—	46
pH	Porous cellulose tricaetate fiber	Congo-red	Transmission	610	—	—	—	—	1–2 min	59

From Iqbal, T., Fiber optics sensors, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 428.

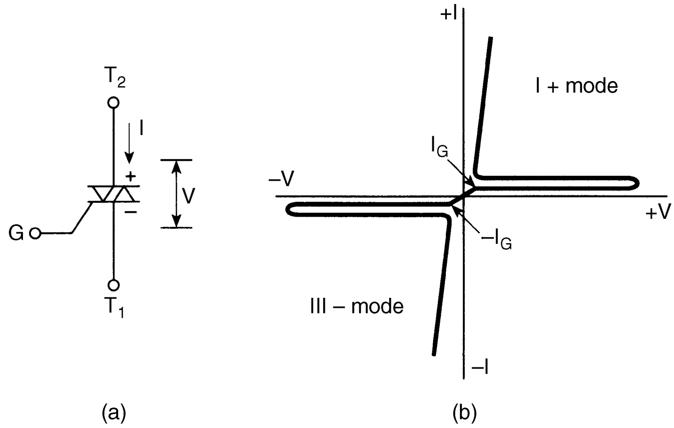
Typical Components of Various Glass Systems

Glass Type	Glass-Forming Systems
Silica glass	Na_2O - Ba_2O_3 -SiO_2
Fluoride glass (ZrF4-based)	$ZrF4_2$-BaF_2-LaF_3-$AlF3_2$-NaF
Fluoride glass (AlF3-based)	AlF_3-BaF_2-CaF_2-YF3-SrF_2-NaF-ZrF_4
Chalcogenide	Ge-As-Se
Chalcohalide	As-S-Cl
Sulphide glass	As_2S_3-La_2S_3

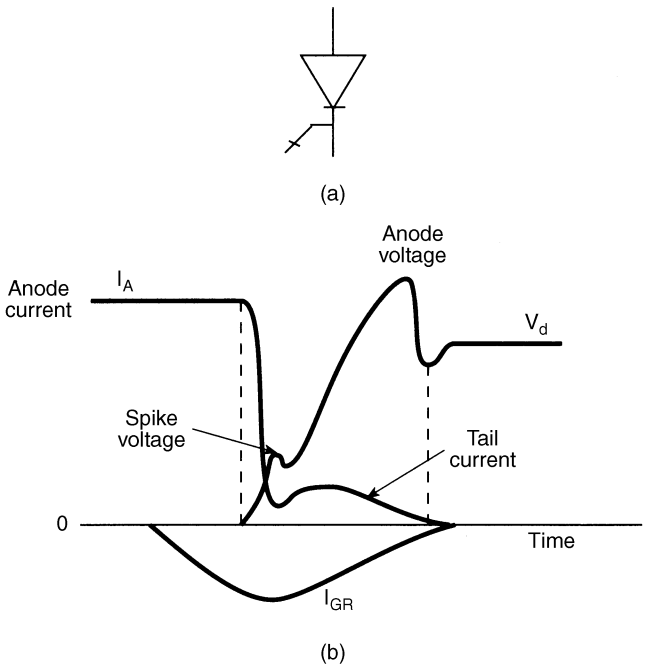
From Iqbal, T., Fiber optics sensors, in *The Handbook of Optical Communication Networks,* Ilyas, M., Ed., CRC Press, Boca Raton, FL, 2003, p. 411.



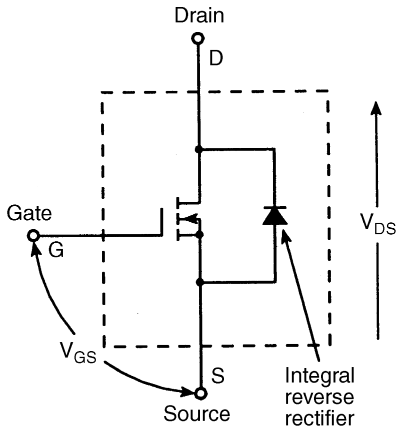
(a) Thyristor symbol and (b) volt-ampere characteristics. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-2. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 5 © 1992 IEEE. With permission.)



(a) Triac symbol and (b) volt-ampere characteristics. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-3. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 5 © 1992 IEEE. With permission.)



(a) GTO symbol and (b) turn-off characteristics. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-4. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 5 © 1992 IEEE. With permission.)



Power MOSFET circuit symbol. (From Rajashekara, K., Overview, in *The Power Electronics Handbook,* Skvarenina, T.L., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-6. Originally from Bose, B.K., *Modern Power Electronics: Evaluation, Technology, and Applications,* p. 7 © 1992 IEEE. With permission.)

Total Elongation at Failure of Selected Polymers

Polymer	Elongation
ABS	5–20
Acrylic	2–7
Epoxy	4.4
HDPE	700–1000
Nylon, type 6	30–100
Nylon 6/6	15–300
Phenolic	0.4–0.8
Polyacetal	25
Polycarbonate	110
Polyester	300
Polypropylene	100–600
PTFE	250–350

From Whitaker, J.C., Fundamental electrical properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 10.

Tensile Strength of Selected Wrought Aluminum Alloys

Alloy	Temper	TS (MPa)
1050	0	76
1050	H16	130
2024	0	185
2024	T361	495
3003	0	110
3003	H16	180
5050	0	145
5050	H34	195
6061	0	125
6061	T6, T651	310
7075	0	230
7075	T6, T651	570

From Whitaker, J.C., Fundamental electrical properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 10.

Density of Selected Materials, mg/m^3

Metal		Ceramic		Glass		Polymer	
Ag	10.50	Al_2O_3	3.97–3.986	SiO_2	2.20	ABS	1.05–1.07
Al	2.7	BN(cub)	3.49	SiO_2 10 wt% Na_2O	2.291	Acrylic	1.17–1.19
Au	19.28	BeO	3.01–3.03	SiO_2 19.55 wt% Na_2O	2.383	Epoxy	1.80–2.00
Co	8.8	MgO	3.581	SiO_2 29.20 wt% Na_2O	2.459	HDPE	0.96
Cr	7.19	SiC(hex)	3.217	SiO_2 39.66 wt% Na_2O	2.521	Nylon, type 6	1.12–1.14
Cu	8.93	$Si_3N_4(\alpha)$	3.184	SiO_2 39.0 wt% CaO	2.746	Nylon 6/6	1.13–1.15
Fe	7.87	Si_3N_4 (β)	3.187			Phenolic	1.32–1.46
Ni	8.91	TiO_2 (rutile)	4.25			Polyacetal	1.425
Pb	11.34	UO_2	10.949–10.97			Polycarbonate	1.2
Pt	21.44	ZrO_2 (CaO)	5.5			Polyester	1.31
Ti	4.51	Al_2O_3 MgO	3.580			Polystyrene	1.04
W	19.25	$3Al_2O_3$ $2SiO_2$	2.6–3.26			PTFE	2.1–2.3

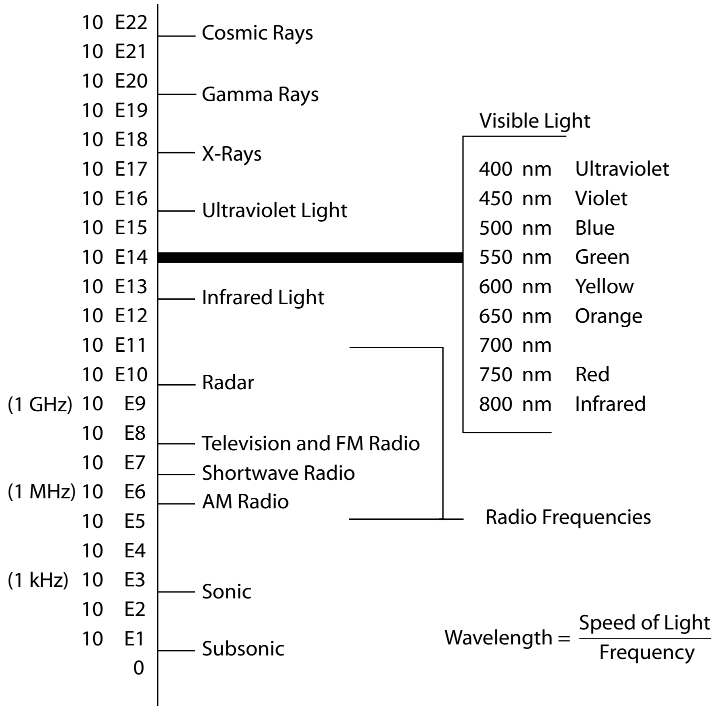
From Whitaker, J.C., Fundamental electrical properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p.11.

Applications in the Microwave Bands

Aeronavigation:	0.96–1.215 GHz
Global positioning system (GPS) down link:	1.2276 GHz
Military communications (COM)/radar:	1.35–1.40 GHz
Miscellaneous COM/radar:	1.40–1.71 GHz
L-band telemetry:	1.435–1.535 GHz
GPS downlink:	1.57 GHz
Military COM (troposcatter/telemetry):	1.71–1.85 GHz
Commercial COM and private line of sight (LOS):	1.85–2.20 GHz
Microwave ovens:	2.45 GHz
Commercial COM/radar:	2.45–2.69 GHz
Instructional television:	2.50–2.69 GHz
Military radar (airport surveillance):	2.70–2.90 GHz
Maritime navigation radar:	2.90–3.10 GHz
Miscellaneous radars:	2.90–3.70 GHz
Commercial C-band satellite (SAT) COM downlink:	3.70–4.20 GHz
Radar altimeter:	4.20–4.40 GHz
Military COM (troposcatter):	4.40–4.99 GHz
Commercial microwave landing system:	5.00–5.25 GHz
Miscellaneous radars:	5.25–5.925 GHz
C-band weather radar:	5.35–5.47 GHz
Commercial C-band SAT COM uplink:	5.925–6.425 GHz
Commercial COM:	6.425–7.125 GHz
Mobile television links:	6.875–7.125 GHz
Military LOS COM:	7.125–7.25 GHz
Military SAT COM downlink:	7.25–7.75 GHz
Military LOS COM:	7.75–7.9 GHz
Military SAT COM uplink:	7.90–8.40 GHz
Miscellaneous radars:	8.50–10.55 GHz
Precision approach radar:	9.00–9.20 GHz
X-band weather radar (and maritime navigation radar):	9.30–9.50 GHz
Police radar:	10.525 GHz
Commercial mobile COM [LOS and electronic news gathering (ENG)]:	10.55–10.68 GHz
Common carrier LOS COM:	10.70–11.70 GHz
Commercial COM:	10.70–13.25 GHz
Commercial Ku-band SAT COM downlink:	11.70–12.20 GHz
Direct broadcast satellite (DBS) downlink and private LOS COM:	12.20–12.70 GHz
ENG and LOS COM:	12.75–13.25 GHz
Miscellaneous radars and SAT COM:	13.25–14.00 GHz
Commercial Ku-band SAT COM uplink:	14.00–14.50 GHz
Military COM (LOS, mobile, and Tactical):	14.50–15.35 GHz
Aeronavigation:	15.40–15.70 GHz
Miscellaneous radars:	15.70–17.70 GHz
DBS uplink:	17.30–17.80 GHz

From Whitaker, J.C., Electromagnetic spectrum, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 31.

The Electromagnetic Spectrum



From Whitaker, J.C., Light, vision, and photometry, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 154.

Typical Luminance Values

Illumination	Illuminance, ft-L
Sun at zenith	4.82×10^8
Perfectly reflecting, diffusing surface in sunlight	9.29×10^3
Moon, clear sky	2.23×10^3
Overcast sky	$9–20 \times 10^2$
Clear sky	$6–17.5 \times 10^2$
Motion-picture screen	10

From Whitaker, J.C., Light, vision, and photometry, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 166. After Fink, D.G., *Television Engineering*, 2nd ed., McGraw-Hill, New York, 1952.

Resistivity of Selected Ceramics

Ceramic	Resistivity, Ω · cm
Borides	
Chromium diboride (CrB_2)	21×10^{-6}
Hafnium diboride (HfB_2)	$10 - 12 \times 10^{-6}$ at room temp.
Tantalum diboride (TaB_2)	68×10^{-6}
Titanium diboride (TiB_2) (polycrystalline)	
85% dense	$26.5–28.4 \times 10^{-6}$ at room temp.
85% dense	9.0×10^{-6} at room temp.
100% dense, extrapolated values	$8.7–14.1 \times 10^{-6}$ at room temp.
	3.7×10^{-6} at liquid air temp.
Titanium diboride (TiB2) (monocrystalline)	
Crystal length 5 cm, 39 deg. and 59 deg. orientation with respect to growth axis	$6.6 + 0.2 \times 10^{-6}$ at room temp.
Crystal length 1.5 cm, 16.5 deg. and 90 deg. orientation with respect to growth axis	$6.7 \pm 0.2 \times 10^{-6}$ at room temp.
Zirconium diboride (ZrB_2)	9.2×10^{-6} at 20°C
	1.8×10^{-6} at liquid air temp.
Carbides: boron carbide (B_4C)	0.3–0.8

From Whitaker, J.C., Resistors and resistive materials, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 187.

Properties of Magnetic Materials and Magnetic Alloys

Material (Composition)	Initial Relative Permeability, μ_i/μ_0	Maximum Relative Permeability, μ_{max}/μ_0	Coercive Force H_e, A/m (Oe)	Residual Field B_r, Wb/m² (G)	Saturation Field B_s, Wb/m² (G)	Electrical Resistivity $\rho \times 10^{-8}$ Ω · m	Uses
			Soft				
Commercial iron (0.2 imp.)	250	9000	≈80 (1)	0.77 (7700)	2.15 (21,500)	10	Relays
Purified iron (0.05 imp.)	10,000	200,000	4 (0.05)	—	2.15 (21,500)	10	
Silicon-iron (4 Si)	1500	7000	20 (0.25)	0.5 (5000)	1.95 (19,500)	60	Transformers
Silicon-iron (3 Si)	7500	55,000	8 (0.1)	0.95 (9500)	2 (20,000)	50	Transformers
Silicon-iron (3 Si)	—	116,000	4.8 (0.06)	1.22 (12,200)	2 (20,100)	50	Transformers
Mu metal (5 Cu, 2 Cr, 77 Ni)	20,000	100,000	4 (0.05)	0.23 (2300)	0.65 (6500)	62	Transformers
78 Peralloy (78.5 Ni)	8000	100,000	4 (0.05)	0.6 (6000)	1.08 (10,800)	16	Sensitive relays
Supermalloy (79 Ni, 5 Mo)	100,000	1,000,000	0.16 (0.002)	0.5 (5000)	0.79 (7900)	60	Transformers
Permendur (50 Cs)	800	5000	160 (2)	1.4 (14,000)	2.45 (24,500)	7	Electromagnets
Mn-Zn ferrite	1500	2500	16 (0.2)	—	0.34 (3400)	20×10^6	Core material for coils
Ni-Zn ferrite	2500	5000	8 (0.1)	—	0.32 (3200)	10^{11}	

From Whitaker, J.C., Inductors and magnetic properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 216. After Plonus, M.A., *Applied Electromagnetic*, McGraw-Hill, New York, 1978.

Thermal Conductivity of Common Materials

Material	Btu/(hu·ft·°F)	W/(m·°C)
Silver	242	419
Copper	228	395
Gold	172	298
Beryllia	140	242
Phosphor bronze	30	52
Glass (borosilicate)	0.67	1.67
Mylar	0.11	0.19
Air	0.015	0.026

From Whitaker, J.C., Thermal properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 234.

Relative Thermal Conductivity of Various Materials As a Percentage of the Thermal Conductivity of Copper

Material	Relative Conductivity
Silver	105
Copper	100
Berlox high-purity BeO	62
Aluminum	55
Beryllium	39
Molybdenum	39
Steel	9.1
High-purity alumina	7.7
Steatite	0.9
Mica	0.18
Phenolics, epoxies	0.13
Fluorocarbons	0.05

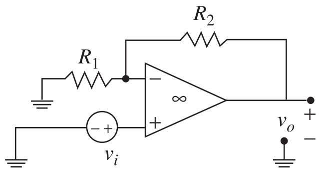
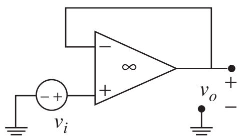
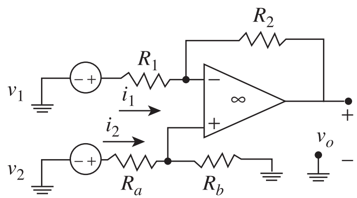
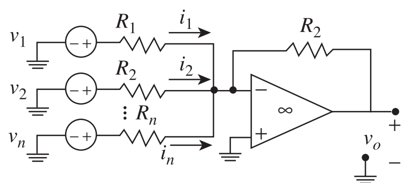
From Whitaker, J.C., Thermal properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 235.

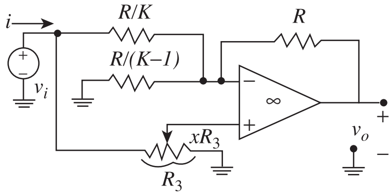
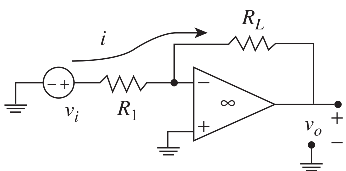
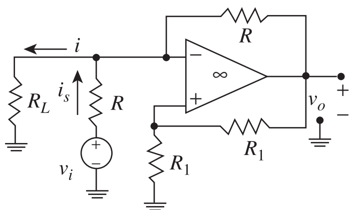
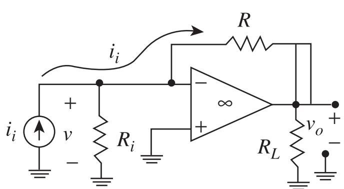
Variation of Electrical and Thermal Properties of Common Insulators As a Function of Temperature

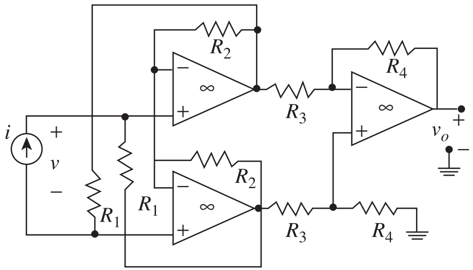
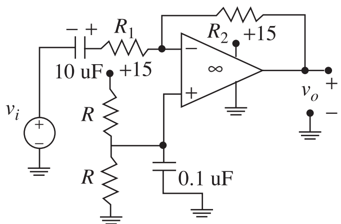
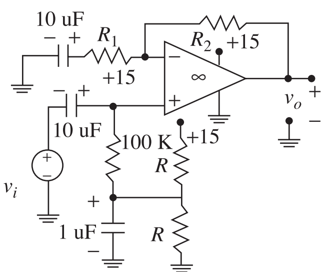
Parameters		20°C	120°C	260°C	400°C	538°C
Thermal conductivity[1]	99.5% BeO	140	120	65	50	50
	99.5% Al_2O_3	20	17	12	7.5	6
	95.0% Al_2O_3	13.5				
	Glass	0.3				
Power dissipation[2]	BeO	2.4	2.1	1.1	0.9	0.7
Electrical resistivity[3]	BeO	10^{16}	10^{14}	5×10^{12}	10^{12}	10^{11}
	Al_2O_3	10^{14}	10^{14}	10^{12}	10^{12}	10^{11}
	Glass	10^{12}	10^{10}	10^{8}	10^{6}	
Dielectric constant[4]	BeO	6.57	6.64	6.75	6.90	7.05
	Al_2O_3	9.4	9.5	9.6	9.7	9.8
Loss tangent[4]	BeO	0.00044	0.00040	0.00040	0.00049	0.00080

[1] Heat transfer in Btu/ft²/hr/°F
[2] Dissipation in W/cm/°C
[3] Resistivity in Ω-cm
[4] At 8.5 GHz

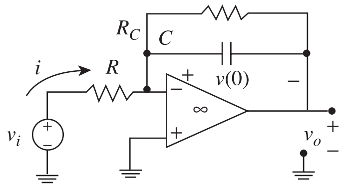
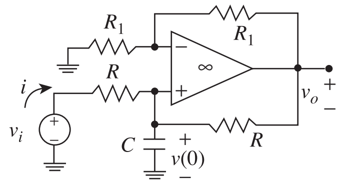
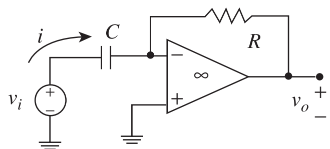
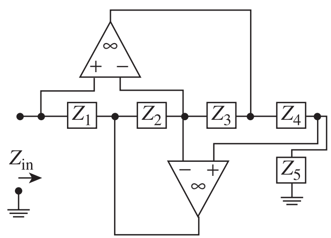
From Whitaker, J.C., Thermal properties, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, p. 239.

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
1.	Noninverting amplifier		$\frac{v_o}{v_i} = 1 + \frac{R_2}{R_1}$	$R_{in} = \infty$ (ideally)	
2.	Buffer		$\frac{v_o}{v_i} = 1$	$R_{in} = \infty$ (ideally)	Special care of circuit 1
3.	Difference amplifier		$v_o = \frac{R_2}{R_1}(v_2 - v_1)$	$i_1 = \frac{v_1 - v_2 \frac{R_b}{(R_a + R_b)}}{R_1}$ $i_2 = \frac{v_2}{R_a + R_b}$	$\frac{R_1}{R_2} = \frac{R_a}{R_b}$
4.	Adder		$v_o = -\left\{v_1 \frac{R_f}{R_1} + v_2 \frac{R_f}{R_2} + \cdots + v_n \frac{R_f}{R_n}\right\}$	$i_1 = \frac{v_1}{R_1}$ $i_2 = \frac{v_2}{R_2}$ $\vdots$ $i_n = \frac{v_n}{R_n}$	

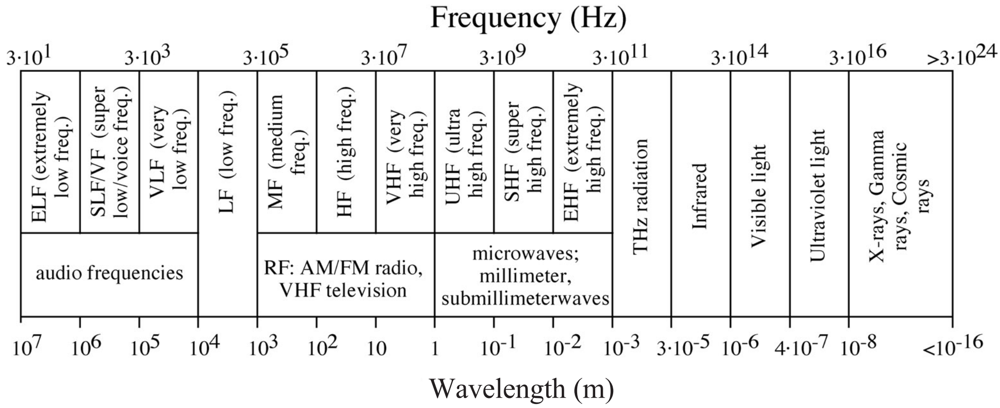
No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
5.	Variable gain circuit		$\frac{v_o}{v_i} = (2Kx - K)$ $0 \le x \le 1, \quad K > 1$	$i = \frac{v_1}{R_3} + \frac{Kv_i(1-x)}{R}$	Potentiometer R_3 adjusts the gain over the range –K to +K.
6.	Voltage-to-current converter		$i = \frac{v_1}{R_1}$		The current through R_L is independent of R_L
7.	Voltage-to-current converter with grounded load		$i = \frac{v_i}{R}$	$i_s = \frac{v_i}{R}\left(1 - \frac{R_L}{R}\right)$	$v_0 = v_i\ (2R_L/R)$. The current i is independent of R_L. Circuit has wide band-with for $R_L \ll R$.
8.	Current-to-voltage converter		$v_0 = Ri_i$	$v = 0$	The voltage v_0 is independent of R_L and R_i

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
9.	Current-to-voltage converter		$v_o = -2iR_1 \frac{R_4}{R_3}$	$v = 0$	
10.	Inverting amplifier with single supply		$v_o = 7.5 - v_i \frac{R_2}{R_1}$		$R = 3.9\ \text{k}\Omega$
11.	Noninverting amplifier with single supply		$v_o = 7.5 + v_i\left(1 + \frac{R_2}{R_1}\right)$		$R = 3.9\ \text{k}\Omega$

Common Op-Amp Circuits (continued)

No.	Type of Circuit	Schematic	Circuit Gain or Variable of Interest	Input Resistance or Input Currents or Voltages	Special Requirements or Remarks
12.	Integrator		$v_o = -V(0) - \frac{1}{RC}\int_0^t v_i(t)dt$ V(0) is the initial voltage across the capacitor. RC is very large.	$i = \frac{v_i}{R}$	Negative feedback is required at DC. A large value of R_C can be used or a feedback path can be established through an external circuit.
13.	DeBoo integrator		$v_o = 2V(0) + \frac{2}{RC}\int_0^t v_i(t)dt$	$i = \frac{v_i}{R} - \frac{v_o}{2R}$	One end of capacitor is physically grounded.
14.	Differentiator		$v_o = -RC\frac{dv_i}{dt}$	$i = C\frac{dv_i}{dt}$	Differentiators are usually avoided in the design of circuits because they accentuate noise.
15.	Generalized impedance converter (GIC)		$Z_{in} = \frac{Z_1 Z_3 Z_5}{Z_2 Z_4}$		

From Whitaker, J.C., Analog circuits, in *The Resource Handbook of Electronics*, CRC Press, Boca Raton, FL, 2001, pp. 267–269.



Electromagnetic frequency spectrum and associated wavelengths. (From Fay, P., Introduction, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **1**-2.)

Modulation Schemes, Glossary of Terms

Abbreviation	Description	Remarks/Use
ACSSB	Amplitude Companded Single SideBand	Satellite transmission
AM	Amplitude Modulation	Broadcasting
APK	Amplitude Phase Keying modulation	
BLQAM	Blackman Quadrature Amplitude Modulation	
BPSK	Binary Phase Shift Keying	Spread spectrum systems
CPFSK	Continuous Phase Frequency Shift Keying	
CPM	Continuous Phase Modulation	
DEPSK	Differentially Encoded PSK (with carrier recovery)	
DPM	Digital Phase Modulation	
DPSK	Differential Phase Shift Keying (no carrier recovery)	
DSB-AM	Double SideBand Amplitude Modulation	
DSB-SC-AM	Double SideBand Suppressed Carrier AM	Includes digital schemes
FFSK	Fast Frequency Shift Keying ≡ MSK	NMT data and control
FM	Frequency Modulation	Broadcasting, AMPS, voice
FSK	Frequency Shift Keying	AMPS data and control
FSOQ	Frequency Shift Offset Quadrature modulation	
GMSK	Gaussian Minimum Shift Keying	GSM voice, data, and control
GTFM	Generalized Tamed Frequency Modulation	
HMQAM	Hamming Quadrature Amplitude Modulation	
IJF	Intersymbol Jitter Free ≡ SQORC	
LPAM	L-ary Pulse Amplitude Modulation	
LRC	LT symbols long Raised Cosine pulse shape	
LREC	LT symbols long Rectangularly EnCoded pulse shape	
LSRC	LT symbols long Spectrally Raised Cosine scheme	
MMSK	Modified Minimum Shift Keying ≡ FFSK	
MPSK	M-ary Phase Shift Keying	
MQAM	M-ary Quadrature Amplitude Modulation	A subclass of DSB-SC-AM
MQPR	M-ary Quadrature Partial Response	Radio-relay transmission
MQPRS	M-ary Quadrature Partial Response System ≡ MQPR	
MSK	Minimum Shift Keying	
m-*h*	multi-*h* CPM	
OQPSK	Offset (staggered) Quadrature Phase Shift Keying	
PM	Phase Modulation	Low capacity radio
PSK	Phase Shift Keying	4PSK ≡ QPSK
QAM	Quadrature Amplitude Modulation	

Modulation Schemes, Glossary of Terms (continued)

Abbreviation	Description	Remarks/Use
QAPSK	Quadrature Amplitude Phase Shift Keying	
QPSK	Quadrature Phase Shift Keying ≡ 4 QAM	Low capacity radio
QORC	Quadrature Overlapped Raised Cosine	
SQAM	Staggered Quadrature Amplitude Modulation	
SQPSK	Staggered Quadrature Phase Shift Keying	
SQORC	Staggered Quadrature Overlapped Raised Cosine	
SSB	Single SideBand	Low and High capacity radio
S3MQAM	Staggered class 3 Quadrature Amplitude Modulation	
TFM	Tamed Frequency Modulation	
TSI QPSK	Two-Symbol-Interval QPSK	
VSB	Vestigial SideBand	TV
WQAM	Weighted Quadrature Amplitude Modulation	Includes most digital schemes
XPSK	Crosscorrelated PSK	
π/4 DQPSK	π/4 shift DQPSK with $\alpha = 0.35$ raised cosine filtering	IS-54 TDMA voice and data
3MQAM	Class 3 Quadrature Amplitude Modulation	
4MQAM	Class 4 Quadrature Amplitude Modulation	
12PM3	12 state PM with 3 bit correlation	

Source: 4U Communications Research Inc., 2000.06.10~00:09, c:/tab/modulat.tab

From Kucar, A.D., Nomadic communications, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-33.

Radar Bands

Band	Frequency Range	Principal Applications
HF	3–30 MHz	Over-the-horizon radar
VHF	30–300 MHz	Long-range search
UHF	300–1000 MHz	Long-range surveillance
L	1000–2000 MHz	Long-range surveillance
S	2000–4000 MHz	Surveillance
		Long-range weather characterization
		Terminal air traffic control
C	4000–8000 MHz	Fire control
		Instrumentation tracking
X	8–12 GHz	Fire control
		Air-to-air missile seeker
		Marine radar
		Airborne weather characterization
Ku	12–18 GHz	Short-range fire control
		Remote sensing
Ka	27– 40 GHz	Remote sensing
		Weapon guidance
V	40–75 GHz	Remote sensing
		Weapon guidance
W	75–110 GHz	Remote sensing
		Weapon guidance

From Belcher Jr., M.L. and Nessmith, J.T., Pulse radar, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **2**-183.

Thermal Conductivities of Typical Metals (W/m K) at Room Temperature

Metal	Thermal Conductivity
Silver	419
Copper	395
Gold	298
Aluminum	156
Brass	101
Lead	32
Kovar	17

From Golio, M., Materials properties — Metals, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-68.

Thermal Coefficient of Linear Expansion of Some of the Materials Used in Microwave and RF Packaging Applications (at Room Temperature, in 10^{-6}/K)

Material	Thermal Coefficient of Expansion
	Dielectrics
Aluminum nitride	4
Alumina 96%	6
Beryllia	6.5
Diamond	1
Glass-ceramic	4–8
Quartz (fuzed)	0.54
	Metals
Aluminum	23
Beryllium	12
Copper	16.5
Gold	14.2
Kovar	5.2
Molybdenum	5.2
Nickel	13.3
Platinum	9
Silver	18.9
	Semiconductors
GaAs	5.9
Silicon	2.6
Silicon Carbide	2.2

From Golio, M., Materials properties — Metals, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-69.

Properties of Some Typical Engineering Insulating Materials

Material	k	Loss	Frequency	Resistivity
Vacuum	1.00	0	All	Zero
Air	1.0006	0		
Glass Vycor 7910	3.8	$9.1 * 10^{-4}$		
Glass Corning 0080	6.75	$5.8 * 10^{-2}$		
Al_2O_3	8.5	10^{-3}	1 MHz	
Teflon (PTFE)	2.0	$2 * 10^{-4}$	1 MHz	10^{17}
Arlon 25N circuit board	3.28	$2.5 * 10^{-3}$	1 MHz	
Epoxy-glass circuit board	4.5			
Beryllium oxide	7.35			
Diamond	5.58			10^{16}
PZT (lead zirconium oxide)	~1000			
Undoped silicon	11.8			
TaO_5	28			
Quartz (SiO_2)	3.75–4.1	$2 * 10^{-4}$		
Mica (Ruby)	6.5–8.7	$3.5 * 10^{-4}$		
Water	78.2	0.04	1 MHz	

From Golio, M., Materials properties — Metals, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-72.

Selected Material Properties of Semiconductors for Microwave and RF Applications

Property	Si	SiC	InP	GaAs	GaN
Atoms/cm^3	5.0×10^{22}	3.95×10^{22}	4.43×10^{22}	4.96×10^{22}	
Atomic weight	28.09	40.1	72.90	72.32	41.87
Breakdown Field (V/cm)	3×10^{5} [32]	20×10^{4} 3C-SiC[27] 30×10^{5} 4H-SiC[27]	5×10^{5} [32]	6×10^{5}	$>10 \times 10^{5}$
Crystal structure	Diamond	Zincblende	Zincblende	Zincblende	Wurtzite
Density (g/cm^3)	2.3283[23]	4.787[23]	5.316[33]	6.1[23]	
Dielectric constant	11.8[23]	9.75[17] 9.66[18]	12.4[23]	12.5[23]	9[35]
Effective mass m^*/m_0 Electron	1.1	0.37 3C-SiC[19] 0.45 6H-SiC[20]	0.067[23]	0.068[23]	0.22[35,36]
Electron Affinity, eV	4.05[31]	—	4.38[31]	4.07[31]	3.4[34]
Energy Gap (eV) at 300 K	1.107[23]	2.403 3C-SiC[23] 3.101 6H-SiC[23]	1.29[31]	1.35[31]	3.34[37]
Intrinsic carrier concentration (cm^{-3})	1.45×10^{10} [23]	3×10^{6} 3C-SiC[21] 10^{15}–10^{16} 6H-SiC[22]	1.6×10^{7} [23]	1.8×10^{6} [23]	$3\text{-}6 \times 10^{9}$ [23]
Lattice constant (Angstroms)	5.431[31]	4.3596[27]	5.860[31]	5.651[31]	3.190[38]
Linear Coeff. of thermal expansion (10^{-6} K^{-1})	2.49[23]	5.48[22]	4.6[23]	5.4[23]	5.6[27]
Melting point (K)	1685[23]	3070[23]	1335[31]	1511[31]	—
Electron mobility (cm^2/V-S) μ_m	1900[23]	1000 3C-SiC[24] 600 6H-SiC[24]	4600[23]	8800[23]	1000[39]
Holes mobility μ_p (cm^2/V-S)	500[23]	40 3C-SiC[24] 40 6H-SiC[24]	150[23]	400[23]	30[39]
Optical phonon energy (eV)	0.063 eV[31]	—	0.43[31]	0.35[31]	.912[40]
Refractive index	3.42[23]	2.65 3C-SiC[25] 2.72 6H-SiC[26]	3.1[31]	3.66[31]	2.7[41] (at band edge)
Resistivity, intrinsic (Ω-cm)	1000[31]	150 3C-SiC[27] $>10^{12}$ 4H-SiC[27]	8.2×10^{7} [31]	3.8×10^{8} [31]	$>10^{13}$ [27]
Specific heat (J/kg°K)	702[23]	640[28]	310[31]	325[32]	847.39[42]
Thermal conductivity at 300°K (Watt/cm°K)	1.24[23]	3.2 3C-SiC[29] 4.9 6H-SiC[30]	0.77[32]	0.56[31]	1.3[43]

From Harris, M., Materials properties — semiconductors, in *The RF and Microwave Handbook,* Golio, M., Ed., CRC Press, Boca Raton, FL, 2001, p. **9**-105.

Channel Designations for VHF and UHF Television Stations in the U.S.

Channel Designation	Frequency Band (MHz)	Channel Designation	Frequency Band (MHz)	Channel Designation	Frequency Band (MHz)
2	54–60	30	566–572	57	728–734
3	60–66	31	572–578	58	734–740
4	66–72	32	578–584	59	740–746
5	76–82	33	584–590	60	746–752
6	82–88	34	590–596	61	752–758
7	174–180	35	596–602	62	758–764
8	180–186	36	602–608	63	764–770
9	186–192	37	608–614	64	770–776
10	192–198	38	614–620	65	776–782
11	198–204	39	620–626	66	782–788
12	204–210	40	626–632	67	788–794
13	210–216	41	632–638	68	794–800
14	470–476	42	638–644	69	800–806
15	476–482	43	644–650	70	806–812
16	482–488	44	650–656	71	812–818
17	488–494	45	656–662	72	818–824
18	494–500	46	662–668	73	824–830
19	500–506	47	668–674	74	830–836
20	506–512	48	674–680	75	836–842
21	512–518	49	680–686	76	842–848
22	518–524	50	686–692	77	848–854
23	524–530	51	692–698	78	854–860
24	530–536	52	698–704	79	860–866
25	536–542	53	704–710	80	866–872
26	542–548	54	710–716	81	872–878
27	548–554	55	716–722	82	878–884
28	554–560	56	722–728	83	884–890
29	560–566				

From Whitaker, J.C., Applications of RF technology, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-16.

Radar Frequency Bands

Name	Frequency Range	Radiolocation Bands based on ITU Assignments in Region II
VHF	30–300 MHz	137–144 MHz
UHF	300–1,000 MHz	216–225 MHz
P-band[b]	230–1,000 MHz	420–450 MHz
		890–940[a] MHz
L-band	1,000–2,000 MHz	1,215–1,400 MHz
S-band	2,000–4,000 MHz	2,300–2,550 MHz
		2,700–3,700 MHz
C-band	4,000–8,000 MHz	5,255–5,925 MHz
X-band	8,000–12,500 MHz	8,500–10,700 MHz
Ku-band	12.5–18 GHz	13.4–14.4 GHz
		15.7–17.7 GHz
K-band	18–26.5 GHz	23–24.25 MHz
Ka-band	26.5–40 GHz	33.4–36 MHz
Millimeter	>40 GHz	

[a] Sometimes included in L-band.
[b] Seldom used nomenclature.

From Whitaker, J.C., Applications of RF technology, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-31. Originally from Fink, D. and Christiansen, Eds., *Electronics Engineers' Handbook*, 3rd ed., McGraw-Hill, New York, 1989, Table 302. IEEE standard 521–1976.

Common-Carrier Microwave Frequencies Used in the U.S.

Band (GHz)	Allotted Frequencies (MHz)	Bandwidth (MHz)	Application
2	2110–2130	20	Limited
	2160–2180		
4	3700–4200	20	Major long-haul microwave relay band
6	5925–6425	500	Long and short haul
11	10,700–11,700	500	Short haul
18	17,700–19,700	1000	Short haul, limited use
30	27,500–29,500	2000	Short haul, experimental

From Whitaker, J.C., Applications of RF technology, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **1**-35.

Comparison of Amplitude Modulation Techniques

Modulation Scheme	Advantages	Disadvantages	Comments
DSB-SC	Good power efficiency. Good low-frequency response.	More difficult to generate than DSB+C. Detection requires coherent local oscillator, pilot, or phase-locked loop (PLL). Poor spectrum efficiency.	
DSB+C (AM)	Easier to generate than DSB-SC, especially at high-power levels. Inexpensive receivers using envelope detection.	Poor power efficiency. Poor spectrum efficiency. Poor low-frequency response. Exhibits threshold effect in noise.	Used in commercial AM.
SSB-SC	Excellent spectrum efficiency.	Complex transmitter design. Complex receiver design (same as DSB-SC). Poor low-frequency response.	Used in military communication systems, and to multiplex multiple phone calls onto long-haul microwave links.
SSB+SC	Good spectrum efficiency. Low receiver complexity.	Poor power efficiency. Complex transmitters. Poor low-frequency response. Poor noise performance.	
VSB-SC	Good spectrum efficiency. Excellent low-frequency response. Transmitter easier to build than for SSB.	Complex receivers (same as DSB-SC).	
VSB+C	Good spectrum efficiency. Good low-frequency response. Inexpensive receivers using envelope detection.	Poor power efficiency. Poor performance in noise.	Used in commercial TV.
QAM	Good low-frequency response. Good spectrum efficiency.	Complex receivers. Sensitive to frequency and phase errors.	Two SSB signals may be preferable.

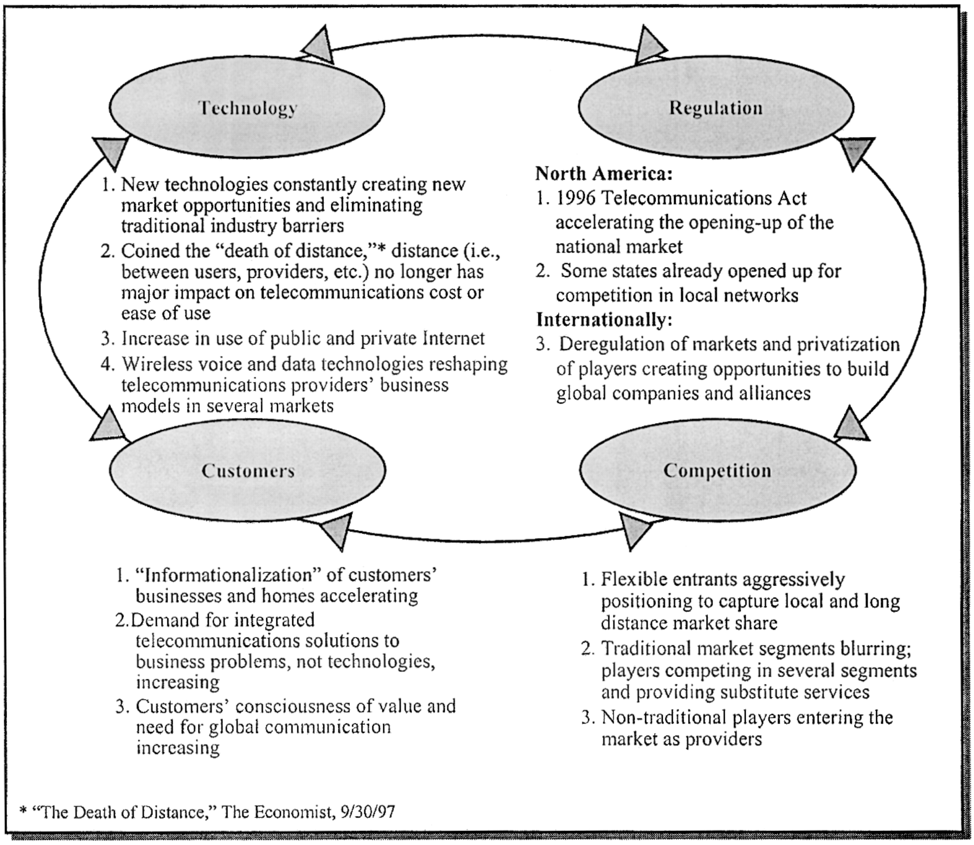
From Kubichek, R., Amplitude modulation, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **3**-14.

Representative Specifications for Various Types of Flexible Air-Dielectric Coaxial Cable

Cable Size (in.)	Maximum Frequency (MHz)	Velocity (%)	Peak Power 1 MHz (kW)	Average Power		Attenuation[a]	
				100 MHz (kW)	1 MHz (kW)	100 MHz (dB)	1 MHz (dB)
1 5/8	2.7	92.1	145	145	14.4	0.020	0.207
3	1.64	93.3	320	320	37	0.013	0.14
4	1.22	92	490	490	56	0.010	0.113
5	0.96	93.1	765	765	73	0.007	0.079

[a] Attenuation specified in dB/100 ft.

From Whitaker, J.C., Coaxial transmission lines, in *The RF Transmission Systems Handbook,* Whitaker, J.C., Ed., CRC Press, Boca Raton, FL, 2002, p. **12**-7.



Four drivers of change in telecommunications. (From Wery, B., Growth strategies for telecommunications operators, in *The Telecommunications Handbook,* Terplan, K. and Morreale, P., CRC Press, Boca Raton, FL, 2000, p. **1**-35.)

Summary and Comparison of Second-Generation TDMA-Based System Parameters

	Europe (GSM)	North America (IS-54/136)	Japan (PDC)
Access method	TDMA	TDMA	TDMA
Carrier spacing	200 kHz	30 kHz	25 kHz
Users per carrier	8 (16)	3 (6)	3 (tbd)
Modulation	GMSK	π/4-DQPSK	π/4-DQPSK
Voice codec	RPE 13 kbps	VSELP 7.95 kbps	VSELP 6.7 kbps
Voice frame	20 ms	20 ms	20 ms
Channel code	Convolutional	Convolutional	Convolutional
Coded bit rate	22.8 kbps	13 kbps	11.2 kbps
TDMA frame duration	4.6 ms	20 ms	20 ms
Interleaving	40 ms	27 ms	27 ms
ACCH	Extra slot	In slot	In slot
Handoff	MAHO	MAHO	MAHO

From Zori, M., Mobile and wireless telecommunications networks, in *The Telecommunications Handbook,* Terplan, K. and Morreale, P., Eds., CRC Press, Boca Raton, FL, 2000, p. **2**-48.

Some Milestones for Multimedia

1982	Introduction of compact disk — consumer audio
1984	Introduction of CD-ROMs; Macintosh GUIs
1986	Initial CD-I (Compact Disk Interactive) specification; Microsoft Windows
1987	DVI (digital video interactive) technology announced
1988	Erasable optical disks; initial ATM standards
1990	MPC (multimedia PC) standard; IMA (Interactive Multimedia Association) Compatibility Project; commercial multimedia applications
1992	ATM-based LAN development (155 Mbps to the desktop); FDDI 100 Mbps connections possible for less than $1000
1994	Wide-area ATM networks; networked multimedia systems and applications
1995	New low-speed voice compression standards (e.g., G.729, G.723.1, G.729A) and other interoperability standards for desktop multimedia are developed; also, DVD launched, H.323 developed
1998	Increased penetration of multimedia in corporate America for "mission-critical" applications; by then, IP had become ubiquitous in intranets and in the Internet; multimedia over LANs sees penetration

From Minoli, D., Minoli, E., and Sookchand, L., Video communications, in *The Telecommunications Handbook,* Terplan, K. and Morreale, P., Eds., CRC Press, Boca Raton, FL, 2000, p. **4**-8.

Comparison of Interconnect Characteristics for Al and Cu

Material	Specific Resistance (μΩ-cm)	Melting Point (°C)
Al	2.66	660
Cu	1.68	1073

From Shenai, K. and McShane, E., VLSI technology: A system perspective, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-8.

Comparison of High-Permittivity Constant Materials for DRAM Cell Capacitors

Material	Dielectric Constant	Minimum Equivalent Oxide Thickness (nm)
NO	7	3.5 to 4
Ta_2O_5	20–25	2 to 3
BST	200–400	?

From Shenai, K. and McShane, E., VLSI technology: A system perspective, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-11.

Summary of Some Architectures and Applications Possible from a Molecular Computing System

Mechanisms and Architectures	Applications
Light-energy transducing proteins	Biosensors
Light-energy transducing proteins (with controlled switching)	Organic memory storage
Optoelectronic transducing	Pattern recognition and processing
Evolutionary structures	Adaptive control

From Shenai, K. and McShane, E., VLSI technology: A system perspective, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **1**-19.

Comparison of Selected Important Semiconductors of Major SiC Polytypes with Silicon and GaAs

Property	Silicon	GaAs	4H-SiC	6H-SiC	3C-SiC
Bandgap (eV)	1.1	1.42	3.2	3.0	2.3
Relative dielectric constant	11.9	13.1	9.7	9.7	9.7
Breakdown field $N_D = 10^{17}$ cm^{-3} (MV/cm)	0.6	0.6	//*c*-axis: 3.0	// *c*-axis: 3.2 ⊥*c*-axis: >1	>1.5
Thermal conductivity (W/cm-K)	1.5	0.5	3–5	3–5	3–5
Intrinsic carrier concentration (cm^{-3})	10^{10}	1.8×10^6	$\sim 10^{-7}$	$\sim 10^{-5}$	~10
Electron mobility @ $N_D = 10^{16}$ cm^{-3} (cm^2/V-s)	1200	6500	//*c*-axis: 800 ⊥*c*-axis: 800	//*c*-axis: 60 ⊥*c*-axis: 400	750
Hole mobility @ $N_A = 10^{16}$ cm^{-3} (cm^2/V-s)	420	320	115	90	40
Saturated electron velocity (10^7 cm/s)	1.0	1.2	2	2	2.5
Donor dopants and shallowest ionization energy (meV)	P: 45 As: 54	Si: 5.8	N: 45 P: 80	N: 85 P: 80	N: 50
Acceptor dopants and shallowest ionization energy (meV)	B: 45	Be, Mg, C: 28	Al: 200 B: 300	Al: 200 B: 300	Al: 270
1998 Commercial wafer diameter (cm)	30	15	5	5	None

From Neudeck, P.G., SiC technology, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **6**-3.

MEMS Processing Technologies

Process	Physical Dimension Range/ Aspect Ratio	Materials	Etch Stop Techniques	Through-put	Cost
		Subtractive processes			
Bulk micromachining	µm-cm/1:400	Single-crystal silicon, GaAs glass etching	Dopant-selective electrochemical Buried layer	High	Low
Reactive ion etch	µm-mm/1:100	Wide range of materials	Buried layer	Low	High
Laser ablation	1-100 µm/1:50	Various	Timed	Low	High
Electrodischarge machining	2 µm-mm/*	Si, metals	Timed	Low	Med
Precision mechanical cutting	nm-cm/*	PMMA	Tool position	Low	High
Focussed ion beam machining	nm-µm	various	Timed	Low	High
Chemical etching	µm/1:10	Metals, semiconductors, insulators	Timed	High	Low
Ultrasonic machining	25 µm-mm/*	Glass, ceramic, semiconductor, metals	Tool position	Moderate	Moderate
		Additive processes			
Physical vapor depositon	Wide range of materials	Electron beam or thermal evaporation/sputtering	—	Moderate	High
Chemical vapor deposition	Surface micromachining	LPCVD of polysilicon/PSG or sputtered aluminum/ photoresist	Selectivity of sacrificial etch to sacrificial layer to structural layer	High	Moderate
Laser-assisted CVD	nm-µm	Various	—	Low	High
Molecular beam epitaxy	nm	Semiconductors	—	Low	Very high
LIGA	µm-cm	PMMA	—	Low	High
Electroplating into a mold:	µm-mm	Cu, Ag, Au, Fe, permalloy	—	High	Low
	µm-mm/1:10	Polyimide	—	High	Moderate
	µm-mm	SU-8	—	High	Low
	µm-mm	Thick photoresist	—	High	Low

* Function of total geometry.
From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-3.

Materials Properties of LPCVD Deposited MEMS Materials

Material	Growth Conditions	Film Thickness	Property	Value	Comments
			Polysilicon		
MUMPS process		3 μm	Young's modulus	169 ± 6.15 GPa	—
			Tensile strength	1.20 ± 0.15 GPa	
Thick polysilicon	1100°C, SiH_4/B_2H_6 or 610°C, Sitty	2.5-10 μm	Young's modulus Fracture toughness	150 ± 3- GPa 2.3 ± 0.1 MPa √m 280 MPa	Undoped film
Thin polysilicon	565°C, SiH_4, 620°C, SiH_4, 100 mTorr	1 μm	As-deposited residual stress		
CMOS		0.33 μm	Young's modulus	168 ± 7 GPa	—
			Tensile strength	2.11 ± 0.10 GPa	
			Young's modulus	162.8 ± 6 GPa	—
			Intrinsic stress	–350 ± 12 GPa	As deposited
			Intrinsicties	162.8 ± 6 GPa	After 1000°C anneal
			Silicon Nitride		
Standard process	800°C, $SiCl_2H_2lNH_3$	—	Intrinsic stress	~1.2 GPa	
Si-rich, variable stoichiometry	800, 850°C 200, 410 mTorr $SiCl_2H_2$/ NH_3	~0.1 μm	Intrinsic stress	(See Figure 10.10)	—
Silicon-rich, variable stoichiometry	850°C 200 mTorr $SiCl_2H_2/NH_3$	0.25–0.45 μm	Young's modulus		
PECVD				(190 GPa)	

From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-18.

Wafer Bonding Techniques

Bonding Technique	Materials	Surface Treatment	Process	Time	Bond Strength/Comments
Anodic bonding	Silicon/7740 Pyrex glass	Clean	350–450°C ~500–1000V	~1–10 min	1–3 MPa[a]/uniform reliable hermetic bond formed
Silicon-silicon	Si-Si SiO_2-Si and SiO_2/SiO_2	Hydrophobic Hydrophilic	500–1100	hrs	Difficult to avoid voids unless processed at higher temperatures
Borosilicate glass	Si/$Si0_2$ and Si_3N_4		450	30 min	—
Eutectic	Si-Au-SiO_2	Clean and oxide-free	~350	—	148 MPa[b]/Nonuniform bonding area
Solder	SiO_2-Pb/Sn/Ag-SiO_2	Needs solder flux	250–400	min	Large difference in thermal expansion coefficient can lead to mechanical fracture
Glass frit	SiO_2-glass Ag mixture-SiO_2	Clean	~350	<hr	Difficult to form thin layers

From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-32.

Microrelays

Application	Fabrication Process	Drive	Contact On-Resistance	Maximum Current	Off- Resistance/ Breakdown voltage	Switching Time	Insertion Loss
			Electrostatic				
Automated test equipment	Bulk micromachining and anodic bonding	<100 V	<3 Ω	—	—	<20 μs	
Switching	CMOS compatible	1-10 V with DC bias of 30-54 V	—	—	—	<1 ms	
RF to microwave	Surface micromachining	28 V at >50 nA	~0.22 Ω	200 mA	—	—	0.1 db at 4 GHz
RF to microwave	Surface micromachining on GaAs	~30 V	—	—	—	—	0.3 dB at 20 GHz
Switching	Electroplated metal films	24 V	0.05 Ω (initial)	5 mA (single contact); 150 mA (multiple contacts)	>100 V	—	—
Small-signal RF	Surface micromachining	20–100 V [10 μW]	10–80 Ω	1 mA	—	2.6– 20 μs	—
			Thermal				
Switching	MUMPS	7-12 V	2.4 Ω	80 mA	—	—	—
RF impedance matching	Surface micromachining in polysilicon	12 mW	2.1–35.6 Ω	>1 mA	>10^{12} Ω 400 V	<0.5 ms	—
			Magnetic				
Electrical control circuits	Polyimide mold and electroplated metals	180 mA (33 mW)	0.022 Ω	1.2 A	—	0.5–2.5 ms	—

From Hesketh, P.J., Micromachining, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **10**-46.

Electronic Packaging Requirements

Speed • Large bandwidth • Short inter-chip propagation delay	Size • Compact size
Thermal and Mechanical • High heat removal rate • A good match between the thermal coefficients of the dice and the chip carrier	Test and Reliability • Easy to test • Easy to modify • Highly reliable • Low cost
Pin Count and Wireability • Large I/O count per chip • Large I/O between the first and second level package	Noise • Low noise coupling among wires • Good-quality transmission line • Good power distribution

From Khandelwal, P. and Shenai, K., Microelectronics packaging, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **11**-2.

Thermal and Electrical Properties of Materials Used in Packaging

Metals

Metals	Coefficient of Thermal Expansion (CTE) (10^{-6} K^{-1})	Thermal Conductivity (W/cm-K)	Specific Electrical Resistance $10^{-6}\Omega$-cm
Aluminum	23	2.3	2.8
Silver	19	4.3	1.6
Copper	17	4.0	1.7
Molybdenum	5	1.4	5.3
Tungsten	4.6	1.7	5.3

Substrates

Insulating Substrates	Coefficient of Thermal Expansion (CTE) (10^{-6} K^{-1})	Thermal Conductivity (W/cm-K)	Dielectric Constant
Alumina (Al_2O_3)	6.0	0.3	9.5
Beryllia (BeO)	6.0	2.0	6.7
Silicon carbide (SiC)	3.7	2.2	42
Silicon dioxide (SiO_2)	0.5	0.01	3.9

Semiconductors

Semiconductors	Coefficient of Thermal Expansion (CTE) (10^{-6} K^{-1})	Thermal Conductivity (W/cm-K)	Dielectric Constant
Silicon	2.5	1.5	11.8
Germanium	5.7	0.7	16.0
Gallium arsenide	5.8	0.5	10.9

From Khandelwal, P. and Shenai, K., Microelectronics packaging, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **11**-6.

Some Properties of Ceramic Packaging Materials

Property	BeO	AlN	Al_2O_3 (96%)	Al_2O_3 (99.5%)
Density (g/cm^3)	2.85	3.28	3.75	3.8
CTE (ppm/K)	6.3	4.3	7.1	7.1
TC (W/cm-K)	285	180	21	25.1
Dielectric const.	6.7	10	9.4	10.2
Loss tangent	0.0001	0.0005	0.0001	0.0001

From Khandelwal, P. and Shenai, K., Microelectronics packaging, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **11**-6.

Interconnect Technologies

Interconnection Type	Line Width (μm)	Line Thickness (μm)	Line Resistance (ohm/cm)	Maximum Length (cm)
On-chip	0.5–2	0.7–2	100–1000	0.3–1.5
Thin-film	10–25	5–8	1.25–4	20–45
Ceramic	75–100	16–25	0.4–0.7	20–50
Printed circuit board	60–100	30–50	0.06–0.08	40–70
Shielded cables	100–450	35–450	0.0013–0.033	150–500

From Nakhla, M.S., Interconnect modeling and simulation, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **17**-5.

Voltage Buffer Performance

Power Supply	5 V	Dissipation	5 mW
DC gain (no load)	–3.3dB	Bandwidth	140 MHz
Output impedance	75Ω	Min. load resistance	10 KΩ
HD2 (V_{in} = 200 mV_{rms})	1 MHz	–50 dB	
	10 MHz	–49 dB	
	20 MHz	–45 dB	
IM3 (V_{in}=200 mV_{rms})	20 MHz, Δf = 200 KHz	–53 dB	
Slew rate	(Load = 10 pF)	+ 130 V/μs	–72 V/μs
Input referred noise	10 $nV\sqrt{Hz}$		

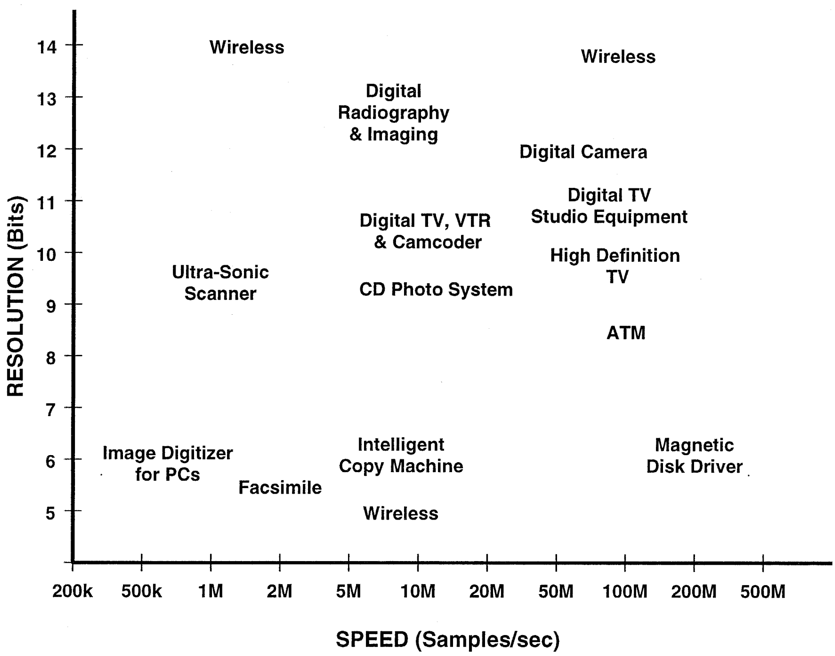
Note: Load = 10 kΩ/10 pF, except for slew rate measurement.

From Toumazou, C. and Payne, A., High-frequency amplifiers, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **21**-7.

Embedded Memory Technologies and Applications

Embedded Memory Technology	Compatibility to Logic Process	Applications
ROM	Diffusion, Vt, Contact programming High compatibility to logic process	Microcode, program storage PAL, ROM-based logic
E/E^{2}prom	High-voltage device, tunneling insulator required	Program, parameter storage, sequencer, learning machine
SRAM	6-Tr/4-Tr single/double poly load cells Wide range of compatibility	High-speed buffers, cache memory
DRAM	Gate capacitor/4-T/planar/ stacked/trench cells Wide range of compatibility	High-density, high bit rate storage

From Wu, C.-Y., Embedded memory, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **50**-4. Originally from Iizuda, T., Embedded memory: A key to high-performance system VLSIs, *Proc. of 1990 Symp. on VLSI Circuts,* pp. 1–4, June 1990.



Recent high-speed ADC applications. (From Song, B.-S., Nyquist-rate ADC and DAC, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **54**-5.)

Microprocessor Statistics

Manufacturer	Part Name	# Transistors (millions)	Frequency (MHz)	Die Size (mm^2)	Technology (μm)
Compaq	Alpha 21264	15.2	600	314	0.35
IBM	PowerPC	6.35	250	66.5	0.3
HP	PA-8000	3.8	250	338	0.5
Sun	Ultrasparc-I	5.2	167	315	0.5
Intel	Pentium II	7.5	450	118	0.25

From Karnik, T., Microprocessor layout method, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **62**-1.

Comparing Electrical Parameters for BJT/HBT vs. FET

Parameter	BJT/HBT	FET
Input impedance Z	Low Z due to forward-biased junction; large diffusion capacitance C_{be}	High Z due to reverse biased junction or insulator; small depletion layer capacitance C_{gs}
Turn-on Voltage	Forward voltage V_{BE} highly repeatable; set by thermodynamics	Pinch-off voltage V_P not very repeatable; set by device design
Transconductance	High g_m $[= I_C/(kT/q)]$	Low g_m $[\cong v_{sat}C_{gs}]$
Current gain	β (or h_{FE}) = 50 to 150; β is important due to low input impedance	Not meaningful at low frequencies and falls as $1/\omega$ at high frequencies
Unity current gain cutoff frequency f_T	$f_T = g_m/2\pi C_{BE}$ is usually lower than for FETs	$f_T = g_m/2\pi C_{gs}$ ($= v_{sat}/2\pi L_g$) higher for FETs
Maximum frequency of oscillation f_{max}	$f_{max} = [f_T/(8\pi r_{b'}C_{bc}]^{1/2}$	$f_{max} = f_T\,[r_{ds}/R_{in}]^{1/2}$
Feedback capacitance	C_{bc} large because of large collector junction	Usually C_{gd} is much smaller than C_{bc}
$1/f$ Noise	Low in BJT/HBT	Very high $1/f$ noise corner frequency
Thermal behavior	Thermal runaway and second breakdown	No thermal runaway
Other		Backgating is problem in semi-insulating substrates

From Estreich, O.B., Compound semiconductor devices for digital circuits, in *The VLSI Handbook,* Chen, W.-K., Ed., CRC Press, Boca Raton, FL, 2000, p. **70**-13.

Status of Conventional and Renewable Power Sources

Conventional	Renewables
Coal, nuclear, oil, and natural gas	Wind, solar, biomass geothermal, and ocean
Fully matured technologies	Rapidly developing technologies
Numerous tax and investment subsidies embedded in national economies	Some tax credits and grants available from some federal and/or state governments
Accepted in society under the 'grandfather clause' as necessary evil	Being accepted on its own merit, even with limited valuation of their environmental and other social benefits

From Patel, M.R., *Wind and Solar Power Systems,* CRC Press, Boca Raton, FL, 1999, p. 3.

Benefits of Using Renewable Electricity

Traditional Benefits	Nontraditional Benefits Per Million kWh consumed
Monetary value of kWh consumed	Reduction in emission
U.S. average 12 cents/kWh	750–1000 tons of CO_2
U.K. average 7.5 pence/kWh	7.5–10 tons of SO_2
	3–5 tons of NOx
	50,000 kWh reduction in energy loss in power lines and equipment
	Life extension of utility power distribution equipment
	Lower capital cost as lower capacity equipment can be used (such as transformer capacity reduction of 50 kW per MW installed)

From Patel, M.R., *Wind and Solar Power Systems,* CRC Press, Boca Raton, FL, 1999, p. 3.

Electromagnetic Radiation and Stable Elementary Particles

	Charge	Mass	Examples or Sources
Alpha particle	+2	4	Alpha "rays" emitted by heavy radioisotopes; cosmic rays
Electron	–1	1/1836	Ionosphere; atoms of matter; beta rays from radioactive elements
Gamma ray	0	0	Radioactive decay; nuclear transitions; nuclear reactors; cosmic rays
Neutrino	0	0	Emitted by sun, stars, nuclear reactors. Accompanies radioactive emission (beta decay)
Neutron[†]	0	1	Vicinity of planets and sun; atomic nuclei; nuclear reactors
Photon	0	0	All light flux from sun, stars, etc.; radiation belts
Positron	+1	1/1836	Fast anti-electrons emitted from radioactive materials
Proton	+1	1	Cosmic rays; radiation belts; atomic nuclei
X-ray	0	0	Radiation belts; solar radiation; high-voltage vacuum tubes

[†] Secondary particle; not stable; life about 1,000 seconds.

Electrons are negatively-charged "atoms of electricity"; in ordinary matter they form an ordered "cloud" surrounding the heavy, positively-charged atomic nuclei.

Photons are electromagnetic waves; they carry energy in discrete quantity, proportional to the frequency of the associated wave.

Beta decay involves the emission of an electron or positron. (The terms *beta-ray* and *beta-particle* are sometimes used.)

Gamma rays consist of high-energy photons (electromagnetic waves); they are emitted in radioactive decay.

X-rays consist of photons emitted in the acceleration (deceleration) of charged particles, as when high-speed electrons strike a heavy, metal target.

Atomic nucleus is the heavy core of the atom, consisting of protons and neutrons. The number of protons is called the *atomic number*. The number of neutrons plus protons is called the *mass number*. The energy required to separate all of the neutrons and protons of the nucleus is called the *binding energy*.

Radioactive nucleus is one that spontaneously changes by radioactive decay, electron capture, or fission. It becomes ultimately transformed into a different kind of nucleus.

Isotopes of an element contain the same number of protons but slightly different numbers of neutrons. They are chemically indistinguishable, except by very much refined procedures and in some biological reactions.

Ions are electrically-charged atoms. If the negative electron charges just balance the total positive charge of the nucleus, the atom is neutral; with more electrons the atom becomes a negative ion, and with fewer electrons it becomes a positive ion.

Fission is the breakup of nuclei into fragments that are themselves nuclei. Mass is usually lost; hence energy is released.

Fusion is the coalescing of two nuclei to form a heavier one.

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 205.

Electromagnetic Frequency Spectra

Ranges and Applications

Application or Common Name	Typical Frequency, cps†	Typical Wavelength‡	Approximate Frequency Range, cps†
Electric a-c power	60	5×10^6 m	25–60
Eddy-current heating (metals)	60	5×10^6 m	50–1000
Servo and instrument power	400	7.5×10^5 m	100–1000
Audio frequency standard	440	6.8×10^5 m	440 and 600
Induction furnace power	2000	1.5×10^5 m	500–3000
R-F heating of metals	10 kc	3×10^4 m	1 kc–1 mc
Power-line communication	30 kc	10^4 m	wide
Maritime and radio beacon	400 kc	750 m	20–550 kc
Radio broadcasting	1000 kc	300 m	550–1600 kc
Shortwave radio	20 mc	15 m	3–300 mc
Microwave diathermy	27 mc	11 m	—
Dielectric heating and drying	40 mc	7.5 m	10–200 mc
F-M radio	100 mc	3m	91–108 mc
Television (channels 2–13)	180 mc	1.67 m	54–216 mc
Radar	500 mc	60.0 cm	200–1200 mc
Television (channels 14–83)	800 mc	37.5 cm	470–890 mc
Tracking stations	960 mc	31.3 cm	440–5600 mc
Intercity relay	2000 mc	15.0 cm	1200–20,000 mc
Radar	10,000 mc	3.0 cm	1200–20,000 mc
Super high frequency	20,000 mc	1.5 cm	3000–30,000 mc
Far infrared (germanium detector)	3×10^{13}	10 μm	
Infrared (PbS detector)	1.25×10^{14}	2.4 μm	
Infrared heaters	1.5×10^{14}	2 μm	
Night infrared searchlight	3×10^{14}	1 μm	
Near infrared photography	3.75×10^{14}	0.8 μm	
Cadmium red line	4.65×10^{14}	.64385 μm	
Yellow (max visual)	5.3×10^{14}	.56 μm	
Solar max intensity	7.1×10^{14}	.42 μm	
Germicidal lamps—ultraviolet	10^{15}	.3 μm	
Soft X-rays	10^{18}	3 Å	
Hard X-rays	10^{20}	.03 Å	
Gamma rays	10^{21}	.003 Å	
Cosmic rays	3×10^{23}	10^{-5} Å	

† The name *hertz* is widely used by electrical engineers for cycles per second.

‡ Units: 1 meter = 100 cm = 39.37 in. = 10^6 micrometers (μm) = 10^{10} angstrom units (Å). Velocity = 186,290 mi/s = 2.99793×10^8 m/s = frequency × wavelength.

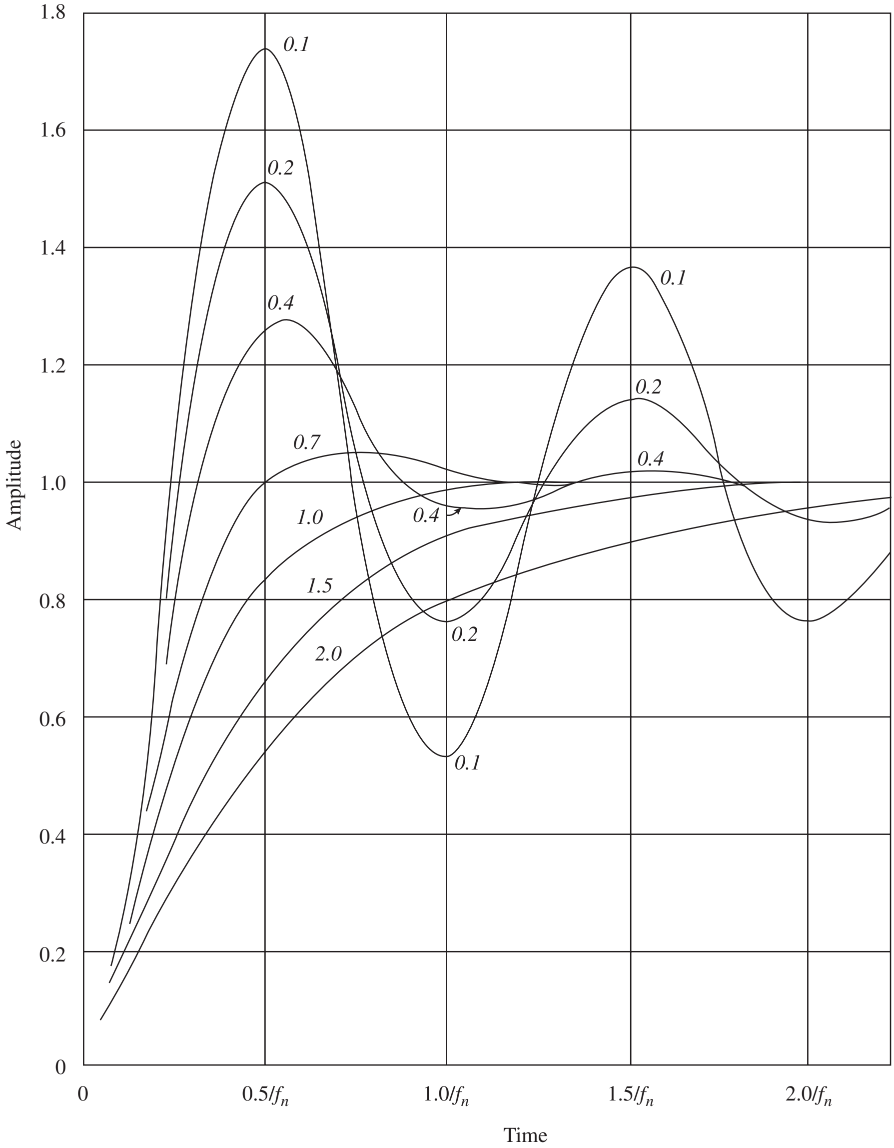
Visible Spectrum — Representative Colors

Color	Frequency	Wavelength
Violet	7.3×10^{14}	0.41
Blue	6.38×10^{14}	0.47
Green	5.75×10^{14}	0.52
Yellow	5.17×10^{14}	0.58
Orange	5.0×10^{14}	0.60
Red	4.6×10^{14}	0.65

From Bolz, R.E. and Tuve, G.L., Electromagnetic radiation, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 206.

Dynamic Response of RCL System to a Step-Change Input

With little or no damping a step-change input will cause an oscillatory RCL system to respond at its natural frequency f_n. The oscillations decrease with time, and this decay may be defined in terms of the logarithmic decrement or exponential decay ratio. At critical damping the response is similar to that of a linear system subjected to the same step input. With large amounts of damping, the response is non-oscillatory



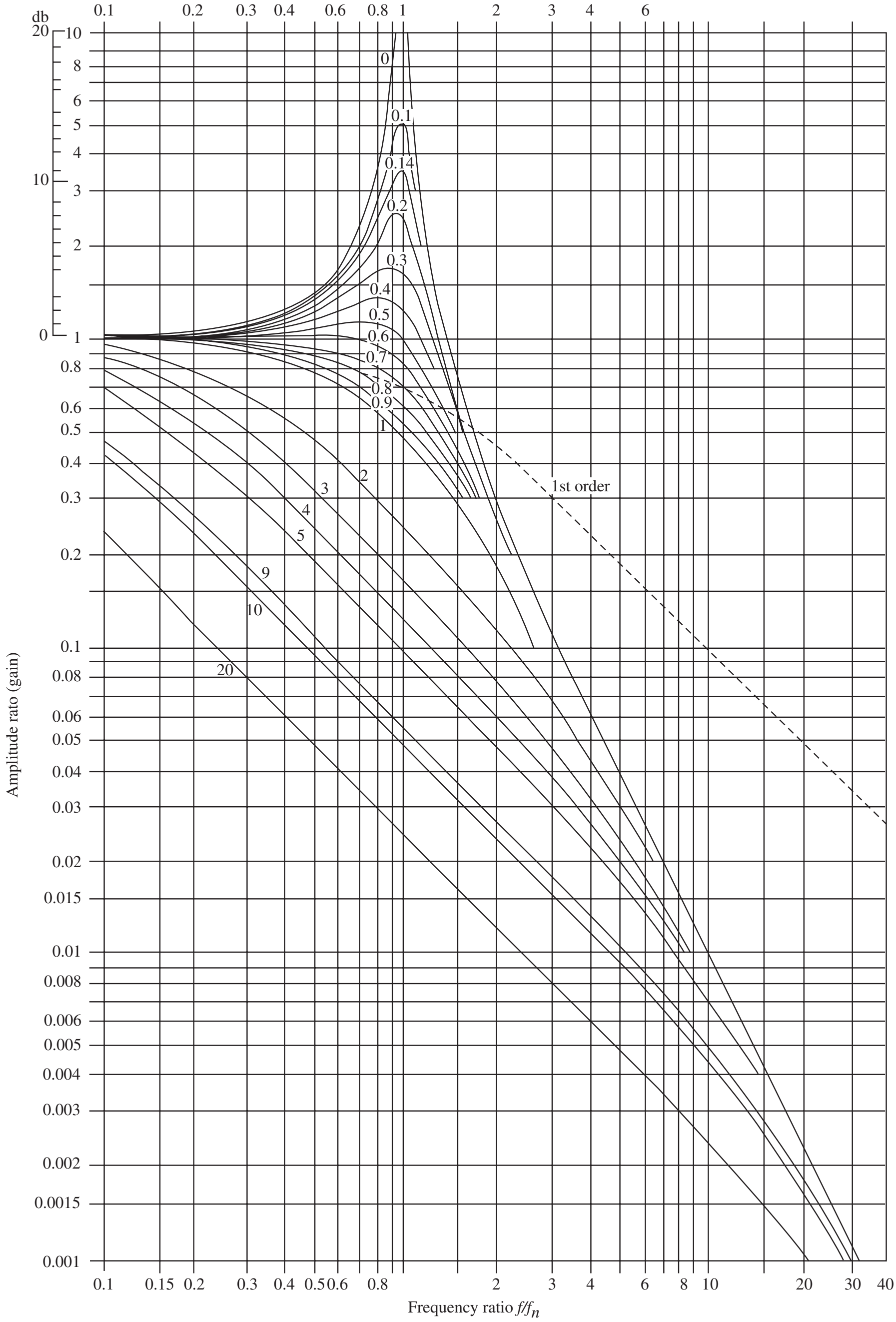
Response of a simple oscillatory system to a unit step input. Damping ratios, $z = c/c_c$, from 0.1 to 2.0.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 598. Originally from Tuve, G.L. and Domholdt, L.C., *Engineering Experimentation*, McGraw-Hill, New York, 1966.

Amplitude Response — Second-Order System

If the input frequency is low, the response of an oscillatory system will almost duplicate the input. At the higher frequencies the response will depend on the ratio of actual damping c to critical damping c_c. For the electrical system critical damping is $2\sqrt{L/C}$; for the mechanical mass-spring-damper system the critical damping is $2\sqrt{km}$, where k is the spring constant and m is the mass.

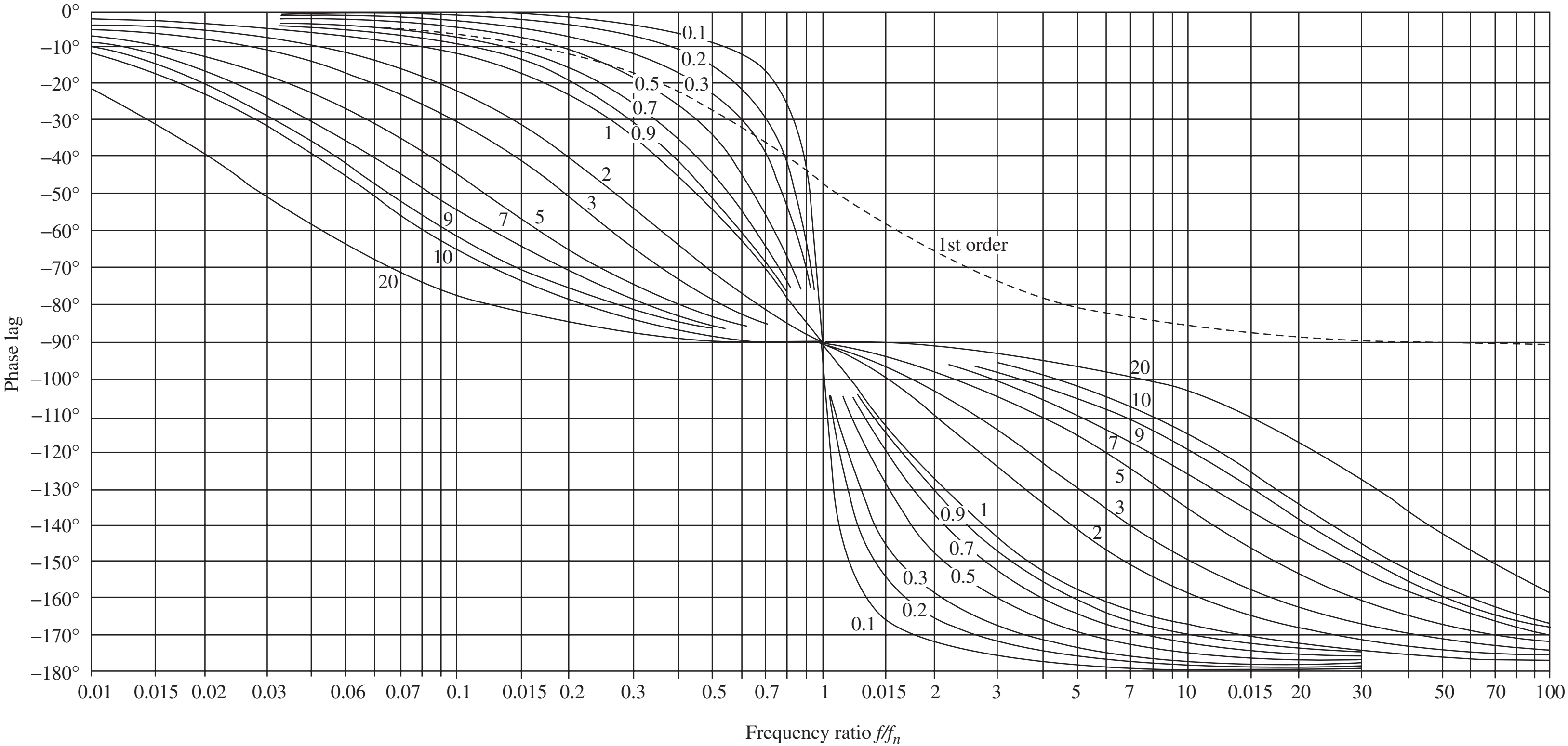
These figures show the response of a simple oscillatory (RCL) system to a sine-wave input, with damping ratios c/c_c from 0.1 to 20.0.



From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 599.

Phase Response—Second-Order System

This figure shows phase lag vs. frequency ratio for a second-order system (RCL) in response to a sine-wave input (semilog coordinates). Damping ratios of 0.1 to 20.0 are given.



Reference

For large-scale curves giving values for damping ratios to 20, frequency ratios to 40, and gains as low as 0.001, see *Handbook of the Engineering Sciences,* J.H. Potter, Ed., Vol. 2, D. Van Nostrand Co., 1967. pp. 786–787.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 600.

Frequency-Response Approximations and Corrections

When the magnitude of the output–input ratio and the phase-angle response are each plotted against frequency on logarithmic coordinates, the work of obtaining the transfer function becomes largely a matter of graphical addition and subtraction. (Semilog plots may also be used.)

A simplification is attained by treating separately each of the four basic types of factors in the transfer function and by starting with straight-line approximations of the actual curves.*

Corrections from the straight-line approximations, to obtain the actual curves, are given in the following table and also in the following figure.

Values of Log Magnitude and Angles of $(1 + j\omega T)^{-1}$

The corner frequency ω_{cf} is used as the index, i.e., $1/(1 + j\omega T) = 1/(1 + j\omega/\omega_{cf})$. Range is one decade above and below ω_{cf}.

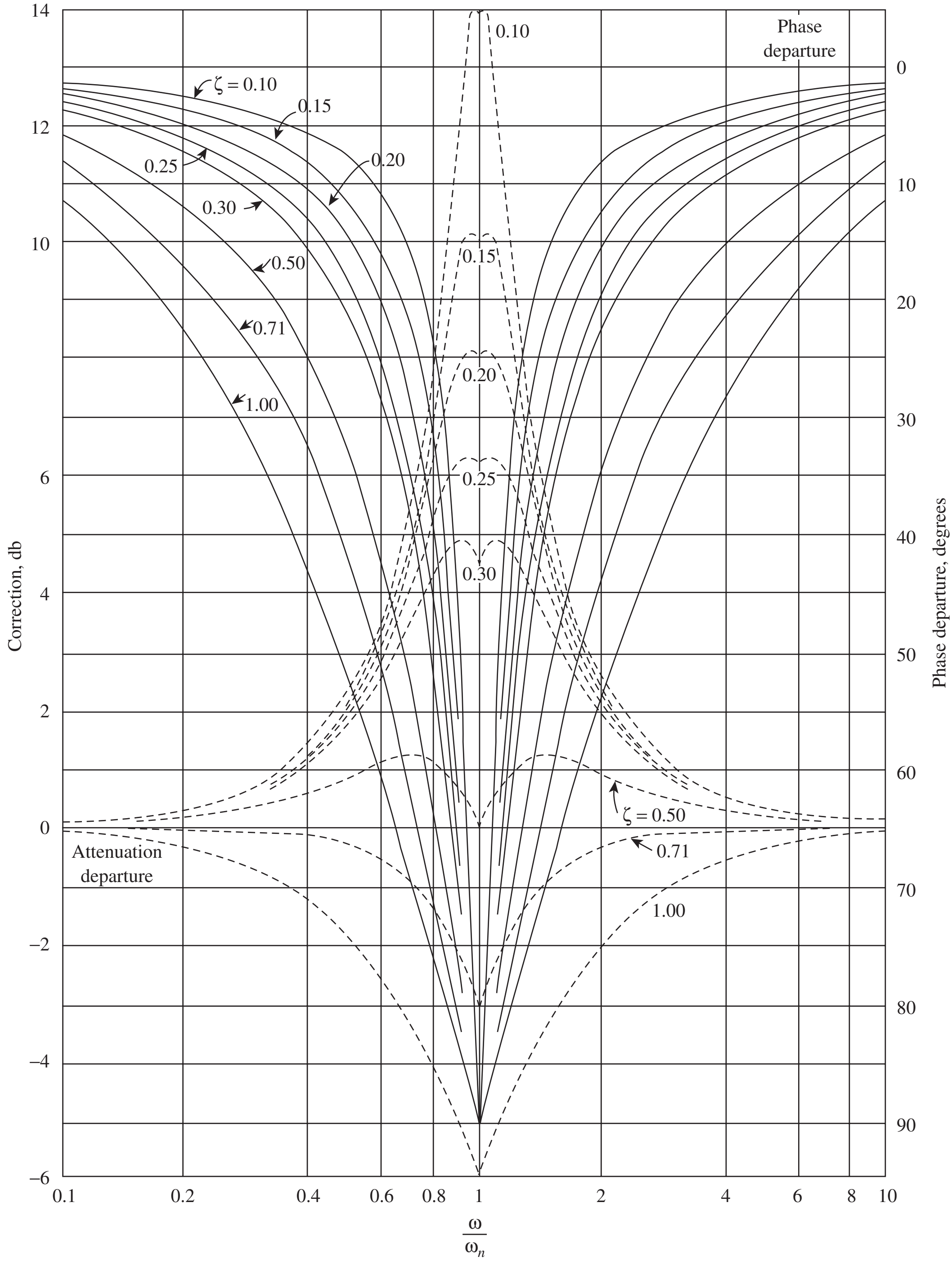
ω_{cf}	Exact Magnitude, db	Value of the Asymptote, db	Error, db	Angle, Degrees
0.10	–0.04	0	–0.04	–5.7
0.50	–0.97	0	–0.97	–26.6
0.76	–2.00	0	–2.00	–45.0
1.00	–3.01	0	–3.01	
1.31	–4.35	–2.35	–2.00	
2.00	–6.99	-6.02	–0.97	–63.4
4.00	–12.30	–12.04	–0.26	
10.00	–20.04	–20.00	–0.04	–84.3

* For a full discussion of the method, with examples, see: *Feedback Control System Analysis and Synthesis,* 2nd ed., J.J. D'Azzo and C.H. Houpis, McGraw-Hill Book Company, New York, 1966, pp. 278–303.

From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 601.

Corrections to the Log Magnitude and Phase Diagram

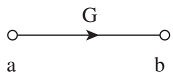
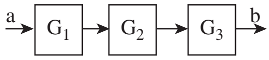
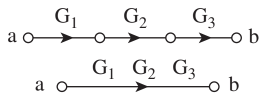
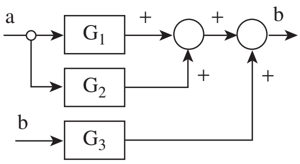
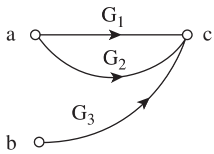
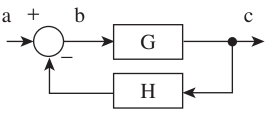
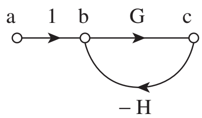
For $[1 + j2z\omega/\omega_n + (j\omega/\omega_n)^2]^{-1}$



From Bolz, R.E. and Tuve, G.L., Dynamics and vibration, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, p. 602. Originally from H.M. James, N.B. Nichols, and R.S. Phillips, *Theory of Servomechanisms*, McGraw-Hill Book Company, New York, 1947.

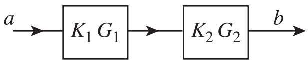
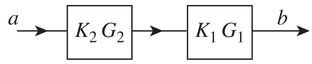
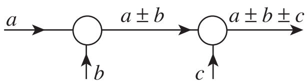
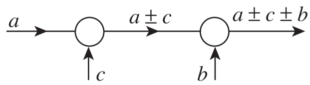
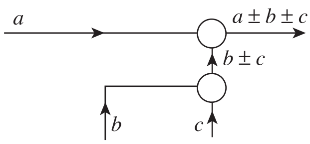
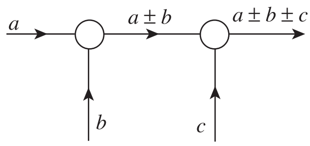
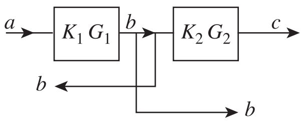
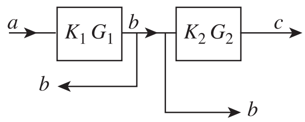
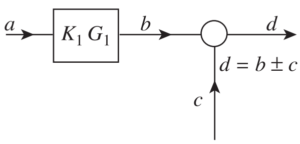
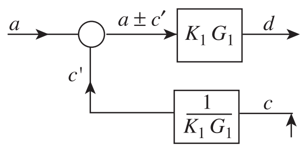
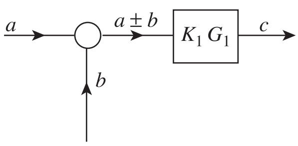
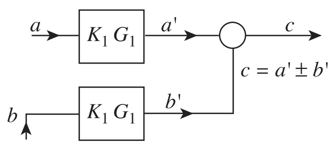
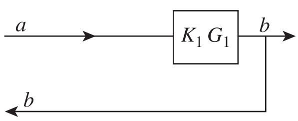
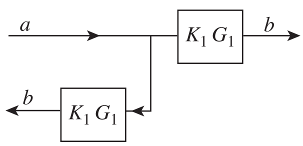
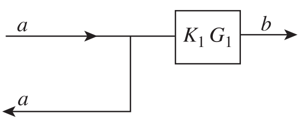
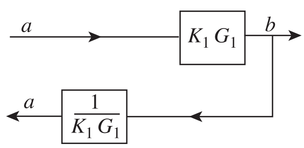
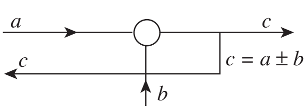
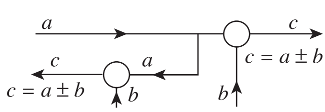
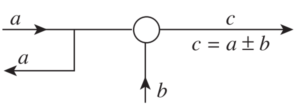
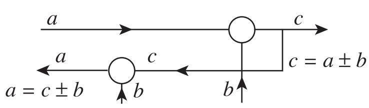
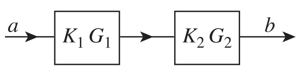
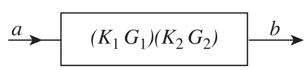
Block and Signal-Flow Diagrams

SYMBOLS: *a* = input
b = output
G = transfer function

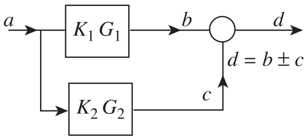
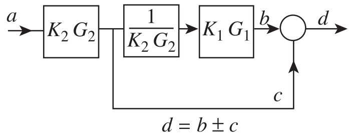
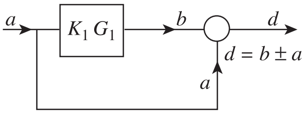
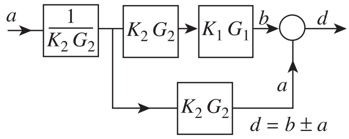
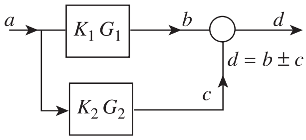
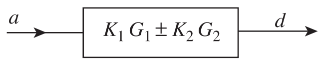
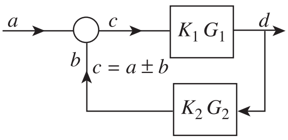
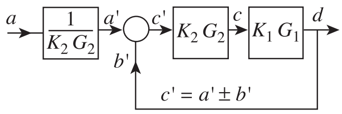
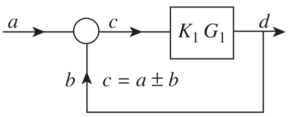
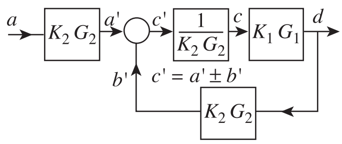
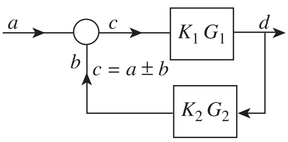
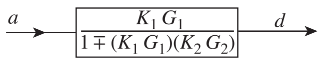
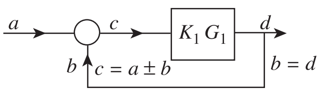
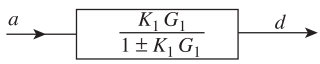
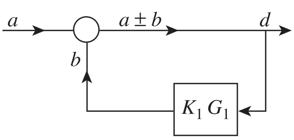
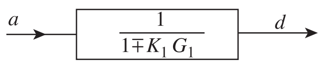
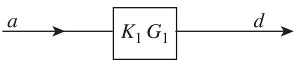
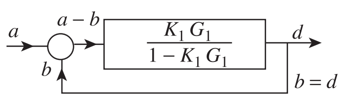
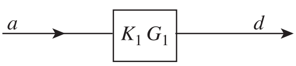
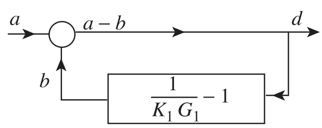
Operation	Block Diagram	Signal-Flow Diagram	Equation
Basic element			$b = Ga$
Elements in cascade			$b = G_1\ G_2\ G_3a$
Elements in parallel			$C = \left(G_1 + G_2\right)a + G_3b -$
Feedback			$C = \dfrac{G}{1+GH}\,a$

From Bolz, R.E. and Tove, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, p. 1061.

Block-Diagram Manipulations

Manipulation	Original Network	Equivalent Network
1. Interchange of elements		
2. Interchange of summing points		
3. Rearrangement of summing points		
4. Interchange of takeoff points		
5. Moving a summing point ahead of an element		
6. Moving a summing point beyond an element		
7. Moving a takeoff point ahead of an element		
8. Moving a takeoff point beyond an element		
9. Moving a takeoff point ahead of a summing point		
10. Moving a takeoff point beyond a summing point		
11. Combining cascade elements		

Block-Diagram Manipulations (continued)

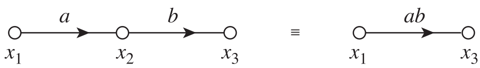
Manipulation	Original Network	Equivalent Network
12. Removing an element from a forward loop		
13. Inserting an element in a forward loop		
14. Eliminating a forward loop		
15. Removing an element from a feedback loop		
16. Inserting an element in a feedback loop		
17. Elminating a feedback loop		
18. Special form of 17		
19. Special form of 17		
20. Inserting a feedback loop to replace an element		
21. Different form of 20		

From Bolz, R.E. and Tove, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 1062–1063. Originally from E.M. Grabbe, S. Ramo, and D.E. Wooldridge, Eds., *Handbook of Automation, Computation, and Control,* Vol. 1, John Wiley & Sons, New York, 1958, pp. **20**-62 and **20**-63.

Signal-Flow Diagrams

Cascade

1.



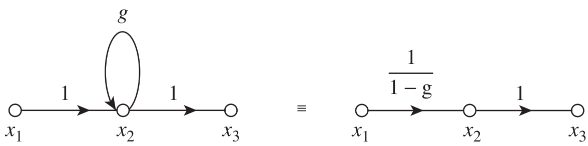
$x_3 = bx_2 = bax_1$

Parallel

2.

$x_2 = (a + b)x_1$

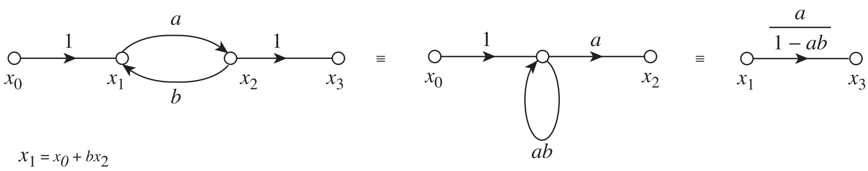
3.



$x_2 = x_1 + gx_2$

$x_2 = x_1\ (1/1\text{-}g)$

4.



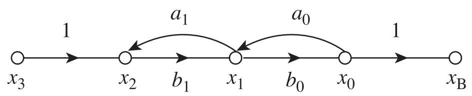
$x_1 = x_0 + bx_2$

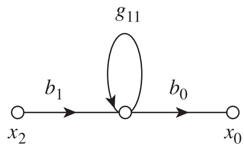
$x_2 = ax_1 = ax_0 + abx_2$

$x_3/x_0 = a/1\text{-}ab$

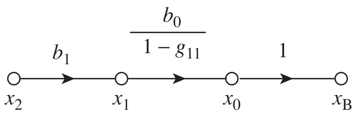
Signal-Flow Diagrams (continued)

5.



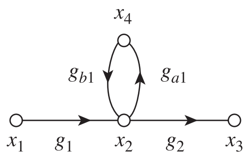


$$g_{11} = a_1b_1 + a_0b_0$$

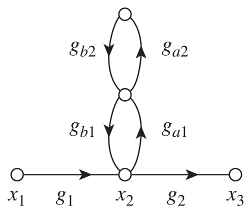


$$\frac{x_B}{x_3} = \frac{b_1b_0}{1 - g_{11}} = \frac{b_1b_0}{1 - a_1b1 - a_0b_0}$$

6.

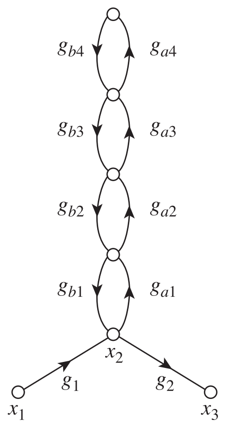


$$\frac{x_3}{x_1} = G = \frac{g_1g_2}{1 - g_{a1}g_{b1}}$$



$$G = \frac{x_3}{x_1} = \cfrac{g_1g_2}{1 - \cfrac{g_{a1}g_{b1}}{1 - g_{a2}g_{b2}}}$$

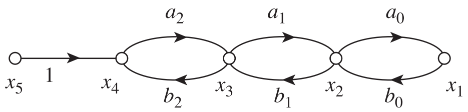
7.



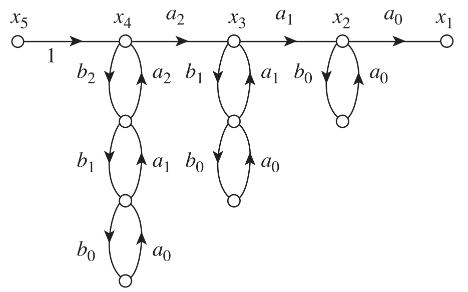
$$G = \frac{x_3}{x_1} = \cfrac{g_1g_2}{1 - \cfrac{g_{a1}g_{b1}}{1 - \cfrac{g_{a2}g_{b2}}{1 - \cfrac{g_{a3}g_{b3}}{1 - g_{a4}g_{b4}}}}}$$

Signal-Flow Diagrams (continued)

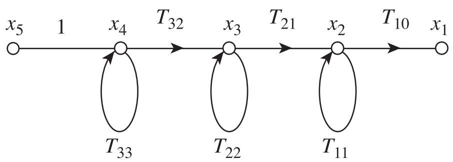
8.



reduces to

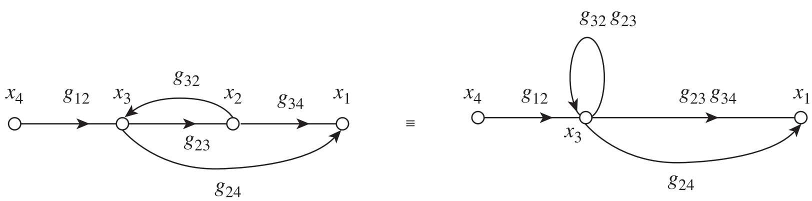


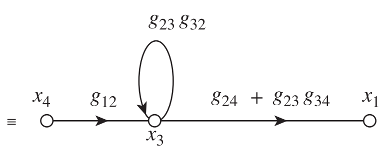
which reduces to



then $$\frac{x_1}{x_5} = a_0\left[\frac{1}{1-a_0b_0}\right]a_1\left[\frac{1}{1-\dfrac{a_1b_1}{1-a_0b_0}}\right]a_2\left[\frac{1}{1-\dfrac{a_2b_2}{1-\dfrac{a_1b_1}{1-a_0b_0}}}\right]$$

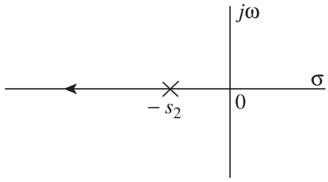
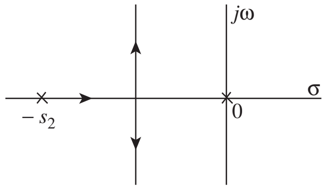
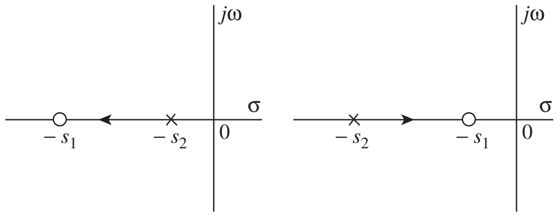
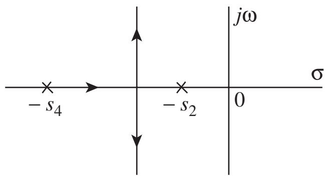
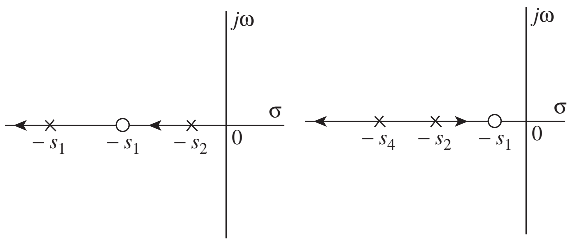
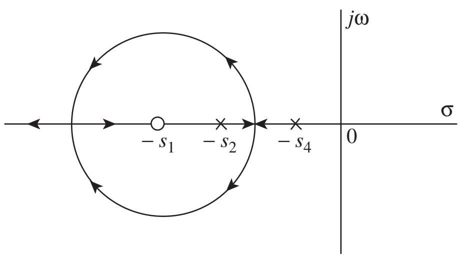
9.



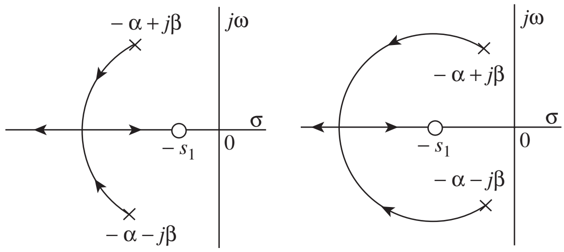
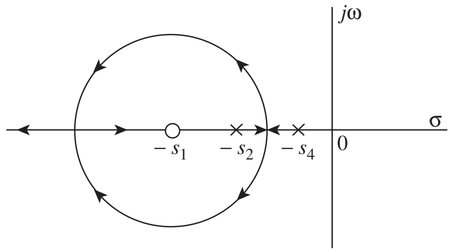
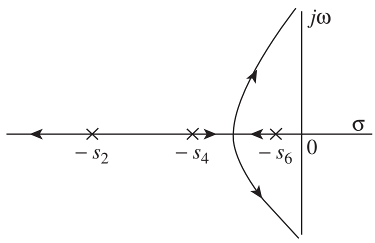
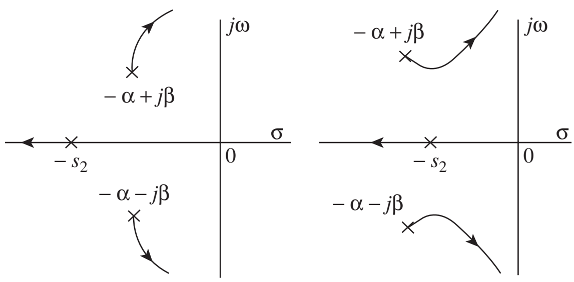
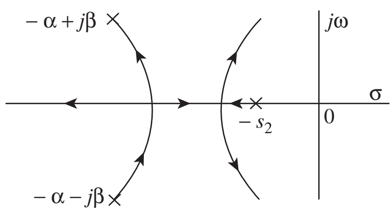


From Bolz, R.E. and Tove, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science,* CRC Press, Boca Raton, FL, 1973, pp. 1064–1066. Originally from D.P. Campbell, *Process Dynamics,* John Wiley & Sons, New York, 1958.

Root Loci

Continuous Systems	
Overall Transfer Function	Sketch of Root Locus
1. $\dfrac{k}{s+s_2}$	
2. $\dfrac{k}{s(s+s_2)}$	
3. $k\dfrac{s+s_1}{s+s_2}$	
4. $\dfrac{k}{(s+s_2)(s+s_4)}$	
5. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)}$	
6. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)}$	

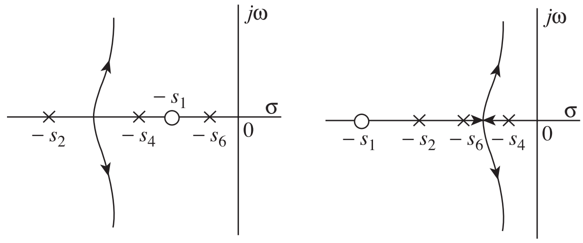
Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus
7. $\dfrac{k(s+s_1)}{(s+\alpha+j\beta)(s+\alpha-j\beta)}$	
8. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)}$	
9. $\dfrac{k}{(s+s_2)(s+s_4)(s+s_5)}$	
10. $\dfrac{k}{(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$	
11. $\dfrac{k}{(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$	

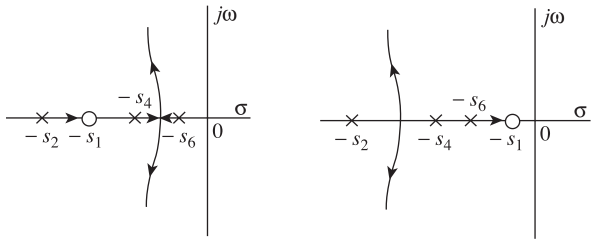
Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus

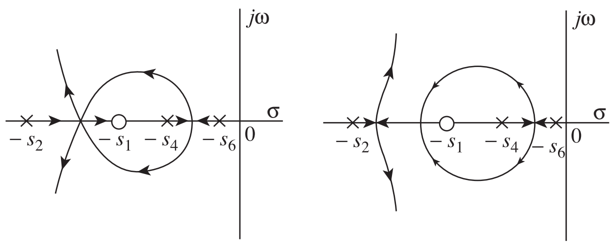
12. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)(s+s_6)}$



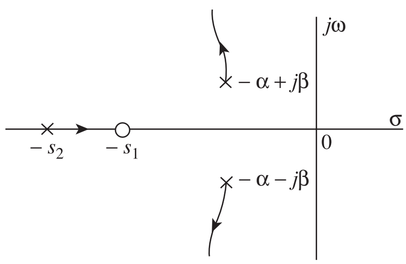
13. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)(s+s_6)}$



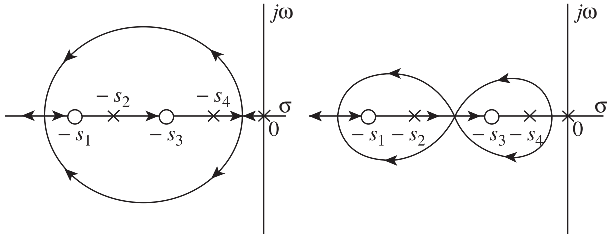
14. $\dfrac{k(s+s_1)}{(s+s_2)(s+s_4)(s+s_6)}$



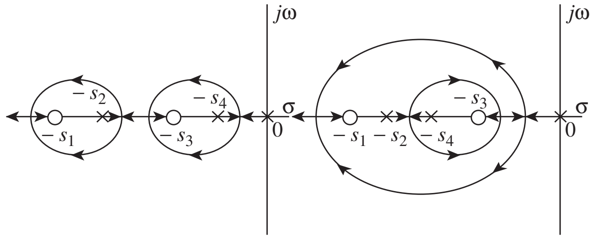
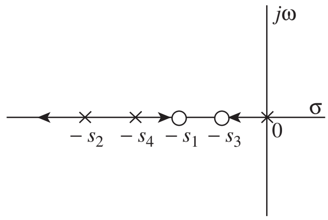
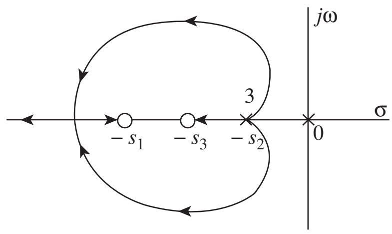
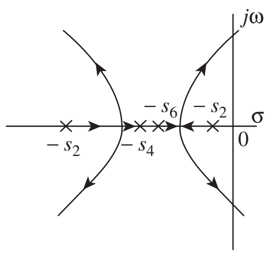
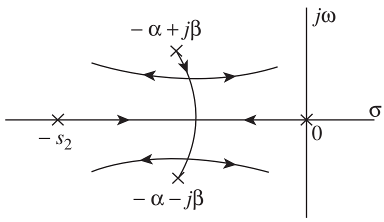
15. $\dfrac{k(s+s_1)}{(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$



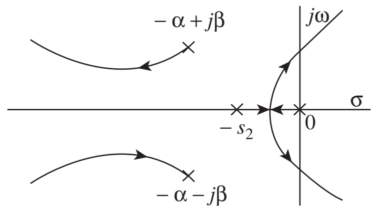
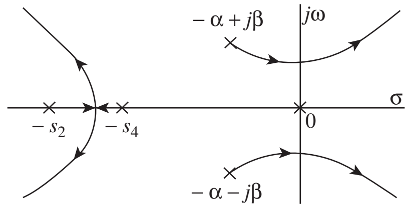
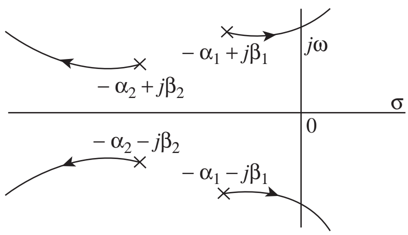
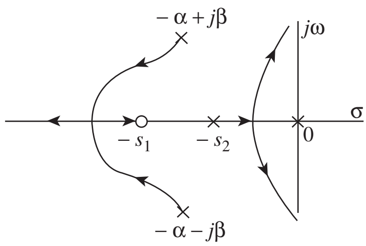
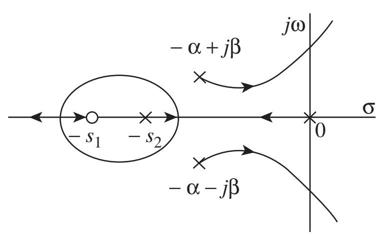
16. $\dfrac{k(s+s_1)(s+s_2)}{s(s+s_2)(s+s_4)}$



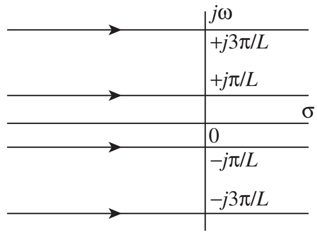
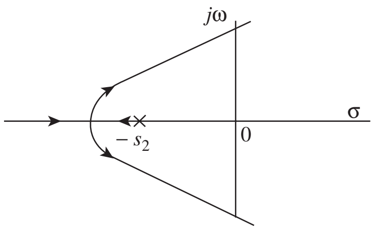
Root Loci (continued)

	Overall Transfer Function	Sketch of Root Locus
17.	$\frac{k(s+s_1)(s+s_3)}{s(s+s_2)(s+s_4)}$	
18.	$\frac{k(s+s_1)(s+s_3)}{s(s+s_2)(s+s_4)}$	
19.	$\frac{k(s+s_1)(s+s_3)}{(s+s_2)}$	
20.	$\frac{k}{(s+s_2)(s+s_4)(s+s_6)(s+s_8)}$	
21.	$\frac{k}{s(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$	

Root Loci (continued)

Overall Transfer Function	Sketch of Root Locus
22. $\dfrac{k}{s(s+s_2)(s+\alpha+j\beta)(s+\alpha-j\beta)}$	
23. $\dfrac{k}{\left\{\begin{matrix}(s+s_2)(s+s_4)(s+\alpha+j\beta)\\ \times(s+\alpha-j\beta)\end{matrix}\right\}}$	
24. $\dfrac{k}{\left\{\begin{matrix}(s+\alpha_1+j\beta)(s+\alpha-j\beta_1)\\ \times(s+\alpha_2+j\beta_2)(s+\alpha_2-j\beta_2)\end{matrix}\right\}}$	
25. $\dfrac{k(s+s_1)}{\left\{\begin{matrix}s(s+s_2)(s+\alpha+j\beta)\\ \times(s+\alpha-j\beta)\end{matrix}\right\}}$	
26. $\dfrac{k(s+s_1)}{\left\{\begin{matrix}s(s+s_2)(s+\alpha+j\beta)\\ \times(s+\alpha+j\beta)\end{matrix}\right\}}$	

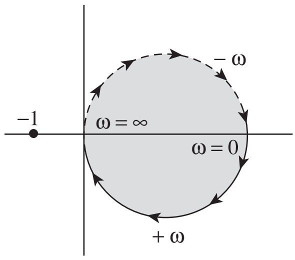
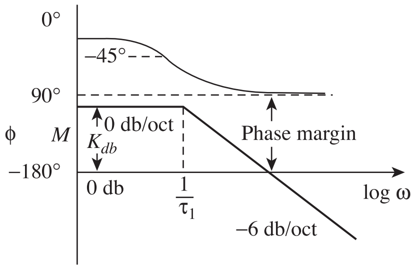
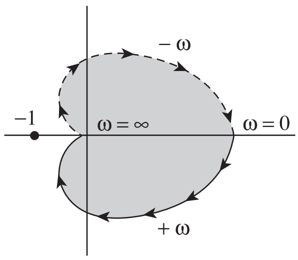
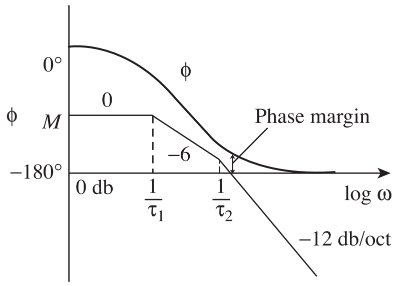
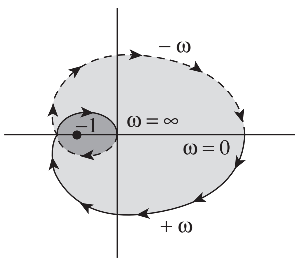
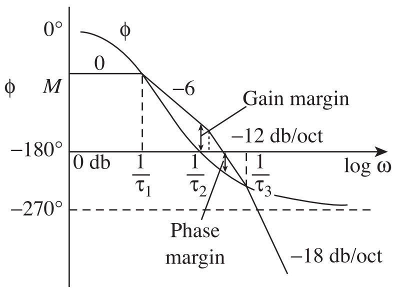
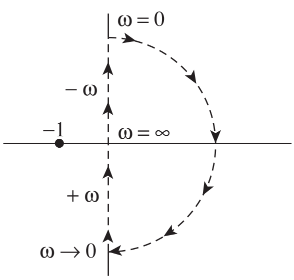
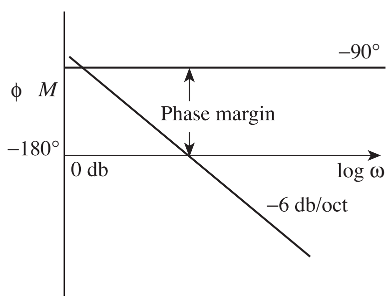
Root Loci (continued)

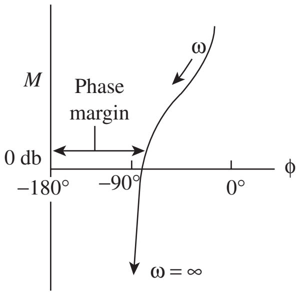
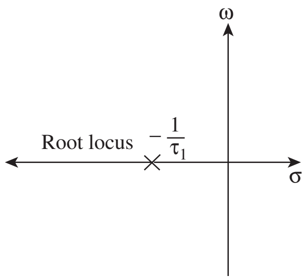
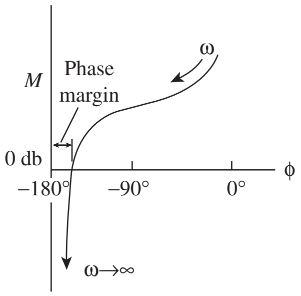
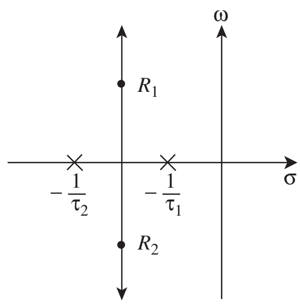
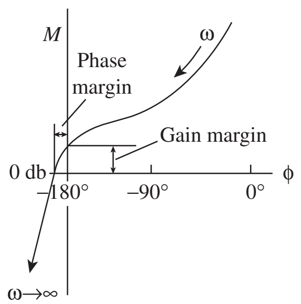
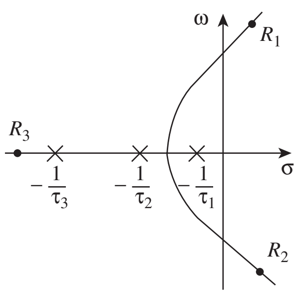
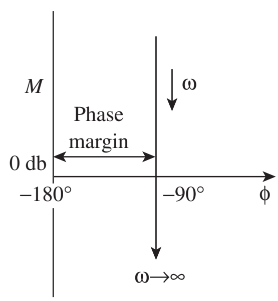
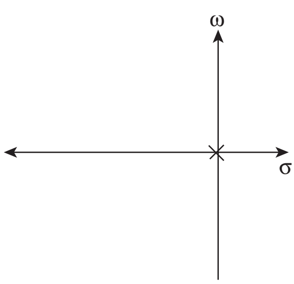
Overall Transfer Function	Sketch of Root Locus
27. ke^{-sL}	
28. $\frac{ke^{-sL}}{s+s_2}$	

Handbook of Automation, Computation and Control, E.M. Grabbe, S. Ramo, and D.E. Wooldridge, Eds., Vol. 1, John Wiley & Sons, New York, 1958.

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1073–1078. Originally from *Mathematics of Automatic Control*, Takahashi, T. (translation edited by George M. Kranc), English translation, Holt, Rinehart and Winston, Inc., New York, 1966.

Transfer Function Plots for Typical Transfer Function

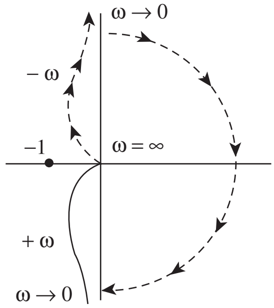
G(s)	Polar Plot	Bode Diagram
1. $\frac{K}{s\tau_1+1}$		
2. $\frac{K}{(s\tau_1+1)(s\tau_2+1)}$		
3. $\frac{K}{(s\tau_1+1)(s\tau_2+1)(s\tau_3+1)}$		
4. $\frac{K}{S}$		

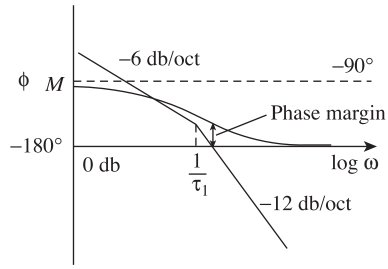
Nichols Diagram	Root Locus	Comments
		Stable; gain margin = ∞
		Elementary regulator; stable; gain margin = ∞
		Regulator with additional energy-storage component; unstable, but can be made stable by reducing gain
		Ideal integrator; stable

Transfer Function Plots for Typical Transfer Function (continued)

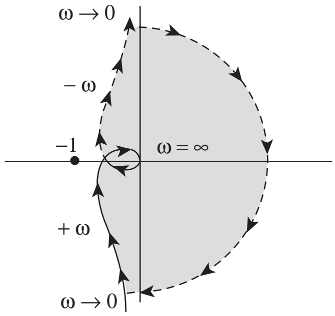
G(s)	Polar Plot	Bode Diagram

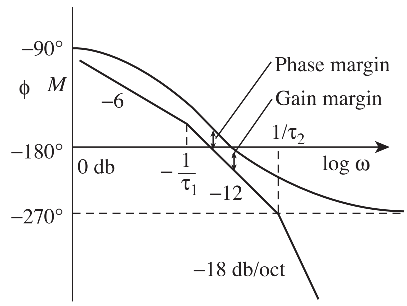
5. $\dfrac{K}{s(s\tau_1+1)}$



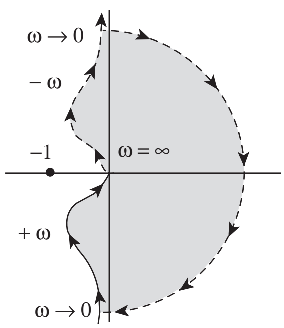


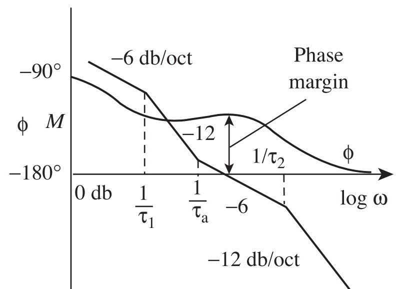
6. $\dfrac{K}{s(s\tau_1+1)(s\tau_2+1)}$



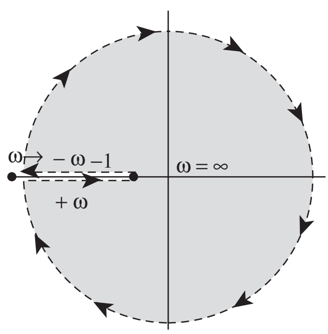


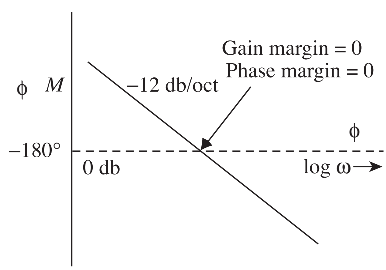
7. $\dfrac{K(s\tau_a+1)}{s(s\tau_1+1)(s\tau_2+1)}$

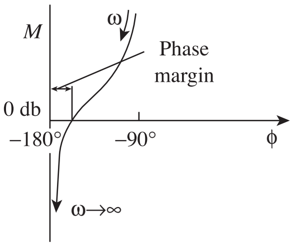
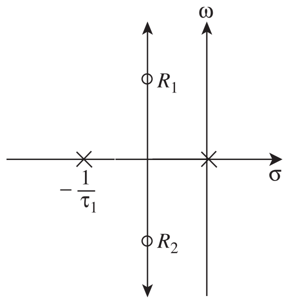
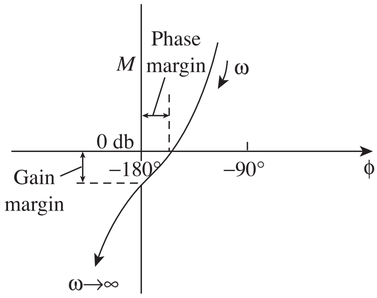
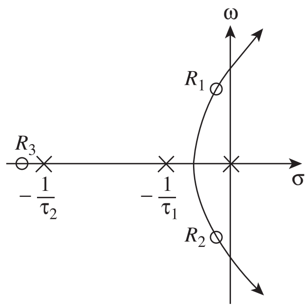
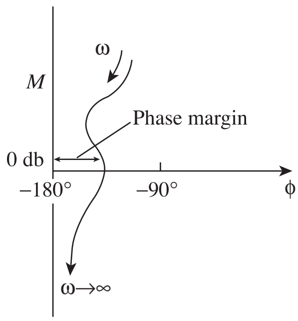
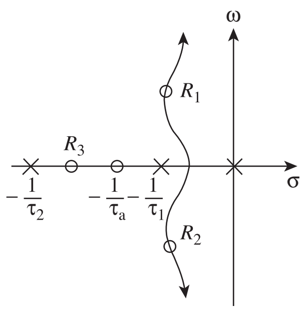
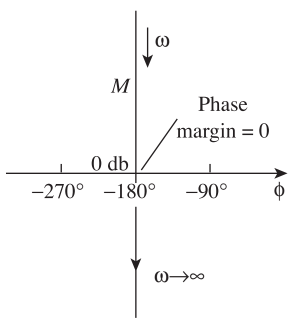
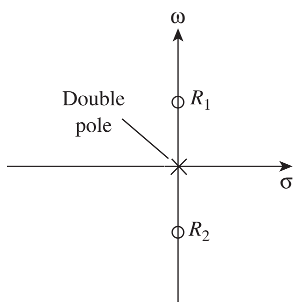




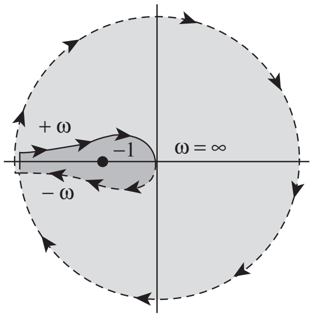
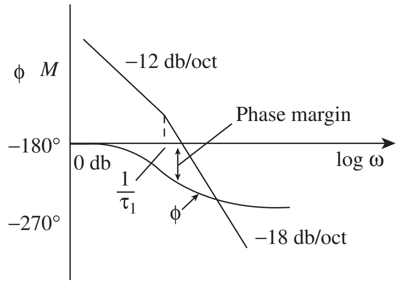
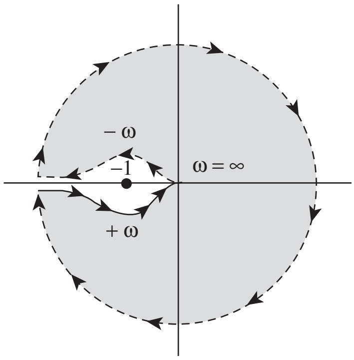
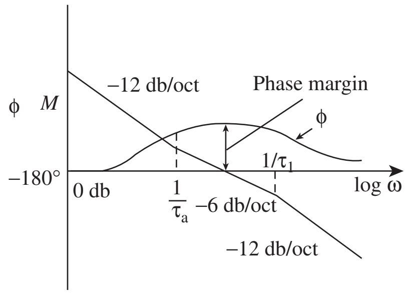
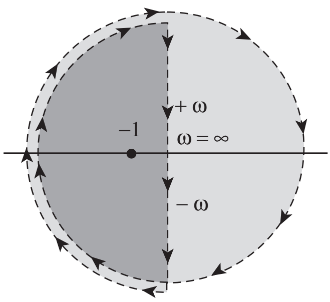
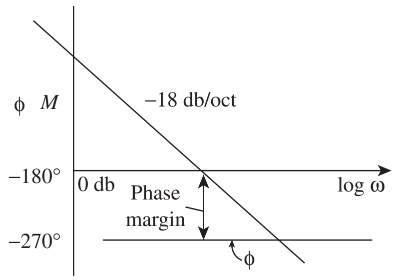
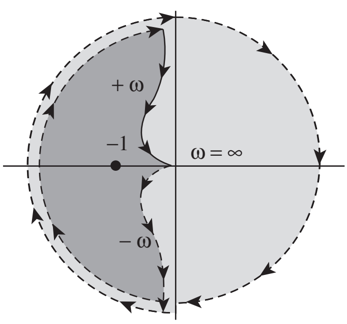
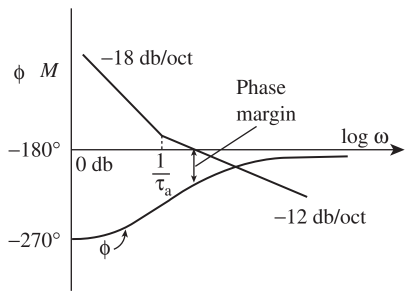
8. $\dfrac{K}{s^3}$

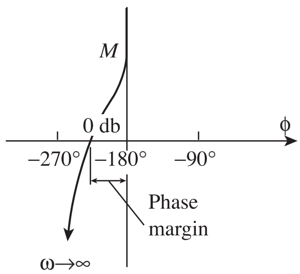
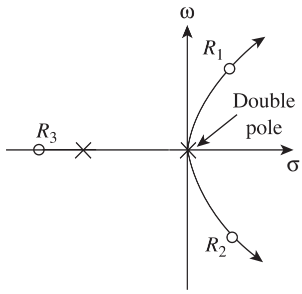
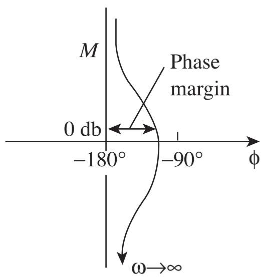
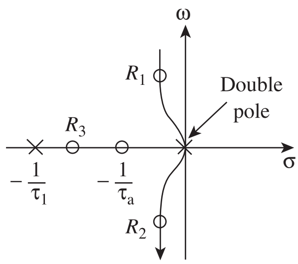
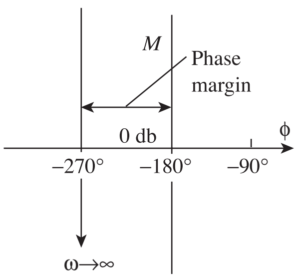
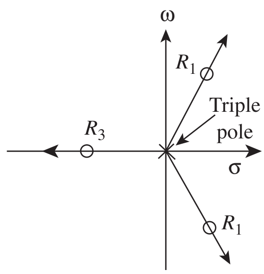
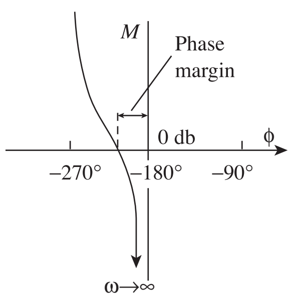
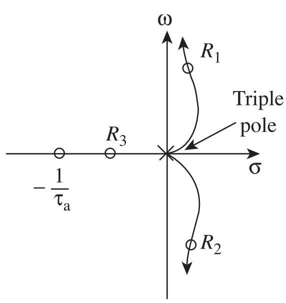




Nichols Diagram	Root Locus	Comments
		Elementary instrument servo; inherently stable; gain margin = ∞
		Instrument servo with field-control motor or power servo with elementary Ward-Leonard drive; stable as shown, but may become unstable with increased gain
		Elementary instrument servo with phase-lead (derivative) compensator; stable
		Inherently unstable; must be compensated

Transfer Function Plots for Typical Transfer Function (continued)

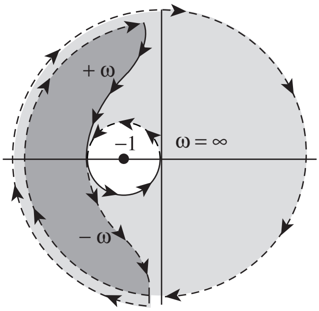
	G(s)	Polar Plot	Bode Diagram
9.	$\frac{K}{s^2(s\tau_1+1)}$		
10.	$\frac{K(s\tau_a+1)}{s^2(s\tau_1+1)}$		
11.	$\frac{K}{s^3}$		
12.	$\frac{K(s\tau_a+1)}{s^3}$		

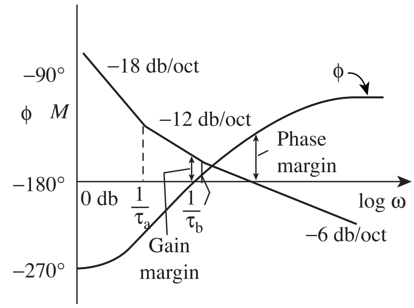
Nichols Diagram	Root Locus	Comments
		Inherently unstable; must be compensated
		Stable for all gains
		Inherently unstable
		Inherently unstable

Transfer Function Plots for Typical Transfer Function (continued)

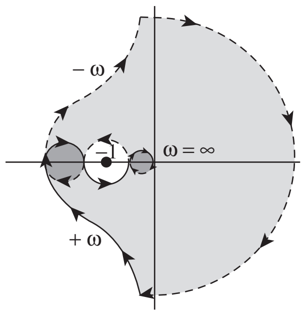
G(s) | Polar Plot | Bode Diagram

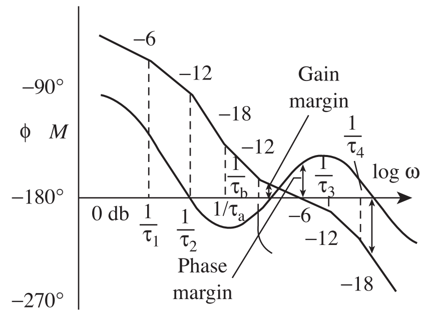
13. $\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s^3}$



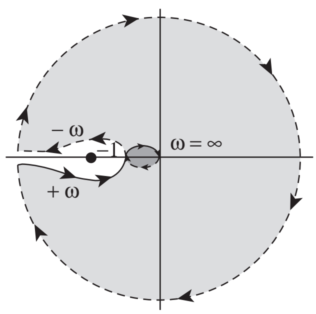


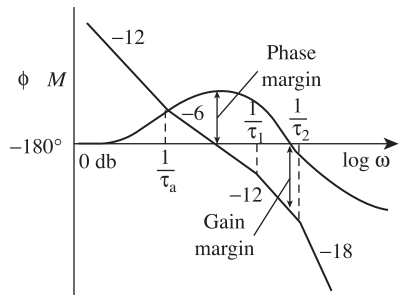
14. $\dfrac{K(s\tau_a+1)(s\tau_b+1)}{s(s\tau_1+1)(s\tau_2+1)(s\tau_3+1)(s\tau_4+1)}$

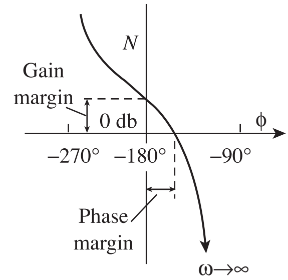
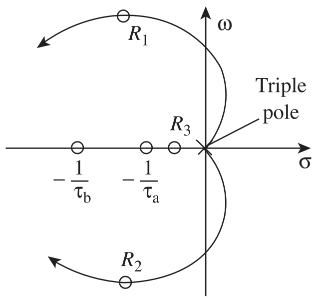
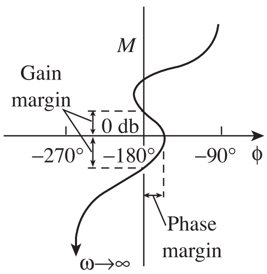
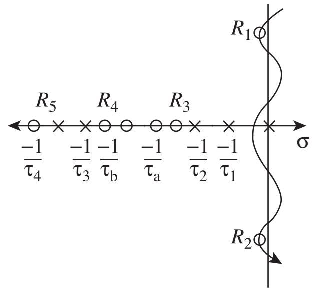
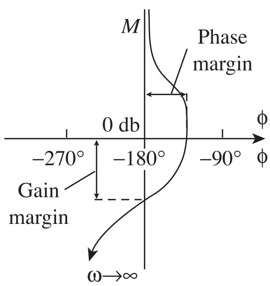
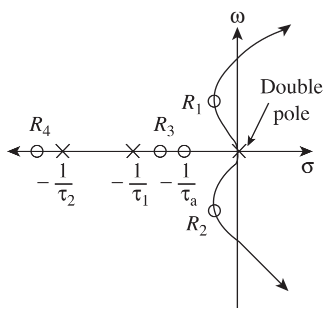




15. $\dfrac{K(s\tau_a+1)}{s^2(s\tau_1+1)(s\tau_2+1)}$





Nichols Diagram	Root Locus	Comments
		Conditionally stable; becomes unstable if gain is too low
		Conditionally stable; stable at low gain, becomes unstable as gain is raised, again becomes stable as gain is further increased, and becomes unstable for very high gains
		Conditionally stable; becomes unstable at high gain

From Bolz, R.E. and Tuve, G.L., Automatic control, in *CRC Handbook of Tables for Applied Engineering Science*, CRC Press, Boca Raton, FL, 1973, pp. 1080–1087. Originally from G.J. Thaler and R.G. Brown, *Analysis and Design of Feedback Control Systems*, 2nd ed., McGraw-Hill Book Company, New York, 1960.