

- Asynchronous sequential circuits (*cont.*)
- design of, 415–416
 - flow table, 420–422
 - fundamental mode, 417
 - hazards, 452–457
 - in combinational circuits, 452–454
 - defined, 452
 - detection of, 453
 - essential, 456–457
 - implementation with SR latches, 454–456
 - remedy for eliminating, 454
 - in sequential circuits, 454
 - implementation example, 430–431
 - laboratory experiment, 553
 - latch excitation table, 430
 - logic diagram, 436–437
 - primitive flow table, 433–435
 - reduction of, 435–436
 - race conditions, 422–424
 - race-free state assignment, 446–452
 - four-row flow-table example, 449–450
 - multiple-row method, 450–452
 - three-row flow-table example, 447–449
 - reduction of state and flow tables, 439–446
 - closed-covering condition, 445–446
 - compatible pairs, 443–444
 - implication table and implied states, 440–442
 - maximal compatibles, 444–445
 - merging of the flow table, 442–443
 - SR latch, 425–427, 430–431
 - analysis example, 428–429
 - transition table, 430
 - stability, 424–425
 - transition table, 417–420, 436–437
 - unstable states:
 - assigning outputs to, 437–439
- Asynchronous sequential logic, 415–470
- B**
- Base, 3–4
- BCD 841, 21–22
- BCD adder, 140–142
 - block diagram, 141
- BCD addition, 19–20
- BCD (binary-coded decimal) code, 18–19
- BCD ripple counters, 256–258
 - logic diagram, 257
 - state diagram, 256
- Behavioral modeling, 168–170, 207–210
- Bidirectional shift register, 251, 537, 537–538
 - with parallel load, 537–538
- Binary adder, 133–134
- Binary adder–subtractor, 129–139
 - binary adder, 133–134
 - binary subtractor, 136–138
 - carry propagation, 134–136
 - full adder, 131–133
 - half adder, 130–131
 - overflow, 138–139
- Binary and decimal numbers (laboratory experiment), 516
 - BCD count, 517–518
 - binary count, 516–517
 - counts, 518
 - oscilloscope display, 517
 - output pattern, 517–518
- Binary cell, 25
- Binary codes, 1, 17–25
 - American Standard Code for Information Interchange (ASCII), 23–25
 - BCD 841, 21–22
 - BCD addition, 19–20
 - BCD (binary-coded decimal) code, 18–19
 - decimal arithmetic, 20–21
 - error-detecting code, 25
 - Excess-3 code, 21–22
 - Gray code, 22–23
 - n -bit binary code, 17–18
 - 2421 code, 21–22
 - weighted codes, 21
- Binary countdown counters, 255
- Binary counter with parallel load, 262–265
 - Clear input, 262–264
 - CLK input, 264
 - Count input, 264
 - Load input, 264
- Binary counters:
 - defined, 253
 - with parallel load, 534–535
- Binary decision box, algorithmic state machines (ASMs), 350
- Binary digits, 1
- Binary logic, 28–31
 - defined, 29
 - logic gates, 30–31
- Binary multiplier, 142–143
 - control state diagram for, 376
 - HDL description of, 382–389
 - datapath unit, 382
 - next-state logic of the controller, 382
 - laboratory experiment, 549–553
 - block diagram, 549–550
 - checking, 552–553
 - control of registers, 550–552
 - datapath design, 552
 - design of control circuit, 552
 - multiplication example, 552
 - parallel multiplier, behavioral
 - description of, 388–390
 - testing, 384–388
- Binary numbers, 3–5
 - conversion to octal numbers, 9
 - signed, 14–17
 - sum of, 5
 - unsigned, 14
- Binary operator, 36
- Binary ripple counters, 253–256
 - binary count sequence, 255
 - defined, 253
 - four-bit, 254
- Binary storage and registers, 25–28
- Binary storage cell, 291–292
- Binary subtractor, 136–138
- Binary systems, 3–4
- Bipolar IC transistors, 477
- Bipolar junction transistor (BJT), 473
- Bipolar transistors:
 - base–emitter graphical
 - characteristic, 479
 - characteristics of, 477–481
 - collector and base currents, 478
 - dc current gain, 479
 - graphical collector–emitter
 - characteristics, 479
 - pulled down output, 479
 - pulled out output, 479
 - saturation region, 479
- Bits, 1, 4, 285
- Bitwise operators, 338
- Block statement, 112
- Blocking assignments, 209–210, 337
- Boole, George, 38
- Boolean algebra, 28, 38
 - associative law, 37
 - axiomatic definition of, 38–39
 - basic theorems, 41–43
 - binary operator, 36
 - canonical forms, 48–55
 - conversion between, 52–53
 - closure, 37
 - commutative law, 37
 - defined, 36, 44
 - distributive law, 37
 - duality, 41
 - field, 37–38
 - identity element, 37
 - inverse, 37
 - and logic gates, 30–31, 36–39
 - manipulation of, 46–47
 - maxterms, 48–50
 - product of, 52

- Control unit, 345–346
- Controllers, 335
- Count operation registers, 334
- Counters:
 - binary countdown counters, 255
 - defined, 242, 253
 - divide-by- N counter, 265
 - HDL for, 269–276
 - Johnson, 268–269
 - laboratory experiment, 533–535
 - binary counter with parallel load, 534–535
 - decimal counter, 534
 - ripple counter, 534
 - synchronous counter, 534
 - ring, 267–268
 - ripple, 253–258
 - BCD, 256–258
 - binary, 253–256
 - symbols, 572–574
 - synchronous, 258–264
 - with unused states, 265–266
- Critical race, 422–423
 - avoiding, 447
 - examples of, 423
- Crosspoint, 300
- Cycle time, memory, 289
- Cycles, 423–424
- Cyclic behavior, 207, 343
 - edge-sensitive, 344
- D**
- D* flip-flops:
 - advantage of designing with, 228
 - analysis of clocked sequential circuits with, 204–206
 - analysis with, 200–201
 - characteristic equation, 194
 - characteristic table, 193–194
 - as example of a sequential machine, 210–212
- D* latch (transparent latch), 187–188
- Darlington pair, 490–491
- Data selector, 154
- Dataflow modeling, 165–167
- DataIn*, 288
- DataOut*, 288
- Datapath unit, 345–346
- Data-processing path, 345–346
- De current gain, 479
- Debounce circuit, 431
- Decade counter, 256
- Decimal adder, 139–142
 - BCD adder, 140–142
- Decimal arithmetic, 20–21
- Decimal counter, 534
- Declaration, 110
- Decoders, 146–149, 566
 - combinational logic
 - implementation, 149
 - n -to- m -line decoders, 146
 - three-to-eight-line, 146
 - truth table for, 147
 - two-to-four-line, with enable input, 147–148
- Delay control operator, 208
- DeMorgan's theorem, 43, 47–48
- Demultiplexer:
 - defined, 148
 - with enable input, 147–148
- Dependency notation, 564–566
- Design:
 - asynchronous sequential circuits, 433–439, 457–463
 - logic diagram, 461–463
 - merging of the flow table, 459–460
 - primitive flow table, 457–458
 - specifications, 457
 - state assignment, 460–461
 - transition table, 460–461
 - combinational circuits, 523
 - with complex programmable logic device (CPLD), 315
 - with *D* flip-flops, 228
 - digital systems, 345
 - electronic design automation (EDA), 65
 - with field-programmable gate array (FPGA), 315
 - multiplexers, 390–401
 - testing the ones counter, 400–401
 - one-hot design (one flip-flop per state), 380–382
 - with programmable array logic (PAL), 309, 311
 - race-free, 401–403
 - software race conditions, 403
 - register transfer example, 352–361
 - algorithmic-based behavioral description, 362
 - behavioral descriptions, 361
 - control logic, 360–361
 - controller and datapath hardware design, 357–358
 - datapath unit, 352
 - HDL description of, 361–370
 - register transfer representation, 358
 - RTL description, 361–365
 - sequence of operations, 356
 - state table, 358–360
 - structural description, 361, 366–370
 - system chart, 353–355
 - testing the design description, 365–366
 - timing sequence, 355–356
 - at register transfer level (RTL), 161, 334–414
 - synchronous sequential logic, 161
 - top-down, 161
- Design entry, 107
- Design procedure, synchronous sequential logic, 225–234
- Digital age, 1
- Digital computers, 1–3
 - general-purpose, 2
- Digital integrated circuits, 471–510
- bipolar transistors:
 - base-emitter graphical characteristic, 479
 - characteristics of, 477–481
 - collector and base currents, 478
 - dc current gain, 479
 - graphical collector-emitter characteristics, 479
 - pulled down output, 479
 - pulled out output, 479
 - saturation region, 479
 - types of, 477
- CMOS transmission gate circuits, 501–504
 - basic circuit of, 501
 - bilateral switch, 501–502
 - connection to inverter, 501–502
 - exclusive-OR gate, construction of, 502–503
 - gated *D* latch, construction of, 503–504
 - master-slave *D* flip-flop, construction of, 504–505
 - multiplexer construction, 503
- complementary MOS (CMOS) circuits, 498–501
 - characteristics of, 500–501
 - CMOS digital logic family, 501
 - CMOS transmission gate circuits, 501–504
 - examples of, 498–500
 - fabrication process, 501
 - graphic symbols, 500
 - inverter, 498
 - two-input NOR gate, 500
- diodes, 479–480
- DTL digital logic family:
 - analysis of, 482–483
 - fan-out, 483

- NAND gate, 482
 - power dissipation of a DTL gate, 483
- emitter-coupled logic (ECL), 493–495
 - basic circuit, 493
 - defined, 493
 - external wired connection of two OR outputs, 495
 - graphic symbol, 495
 - internal temperature- and voltage-compensated bias circuit, 493
 - internal wired connection of two OR outputs, 495
 - propagation delay, 494–495
- metal-oxide semiconductor (MOS), 495–498
 - advantage of, 497
 - basic structure of, 495
 - channel, 495
 - depletion mode, 496
 - diffused channel, 496
 - drain, 495
 - enhancement mode, 496
 - gate, 495
 - graphic symbols, 496
 - n*-channel MOS, 496–497
 - p*-channel MOS, 496–497
 - source, 495–496
 - types of, 496
- RTL digital logic family:
 - analysis of, 481
 - fan-out, 481–482
 - NOR gate, 481
- switch-level modeling, 505–508
 - transmission gate, 506–507
- transistor–transistor logic, 484–493
 - advanced low-power Schottky TTL gate, 485
 - characteristics (table), 484
 - fast TTL family, 485
 - high-speed TTL gate, 484–485
 - low-power Schottky TTL, 485
 - low-power TTL gate, 484
 - open-collector output gate, 485–488
 - original, 484
 - propagation delay, 484
 - Schottky TTL gate, 484–485, 489–491
 - standard, 484
 - three-state gate, 491–493
 - totem-pole output, 488–489
- Digital logic circuits, 27–28
- Digital logic gates, 57–62
 - exclusive-OR gate, 59
 - extension to multiple inputs, 59–61
 - integrated circuits, 63–65
 - computer-aided design, 64–65
 - digital logic families, 63–64
 - levels of integration, 63
 - laboratory experiment, 519–520
 - NAND circuit, 520
 - propagation delay, 519–520
 - truth tables, 519
 - universal NAND gate, 520
 - waveforms, 519
 - NAND function, 59
 - positive and negative logic, 61
 - Digital logic trainers, 511–512
 - Digital systems, 1–3
 - defined, 2, 334
 - logic design of, 345
 - relationship between control logic and data-processing operations in, 345–346
 - Digital versatile disk (DVD), 2
 - Diminished radix, 10
 - Diminished radix complement, 10
 - Diodes, 479–480
 - symbol and characteristic, 480
 - Direct (dedicated) interconnect lines, 317
 - Direct inputs, flip-flops, 194–195
 - Direct reset input, flip-flops, 194
 - Distributed RAM, 317
 - Distributive law, 37
 - Divide-by-*N* counter, 265
 - Don't-care conditions, 86–88
 - DRAM, *See* Dynamic RAM (DRAM)
 - DTL digital logic family:
 - analysis of, 482–483
 - fan-out, 483
 - NAND gate, 482
 - power dissipation of a DTL gate, 483
 - DTL (diode–transistor logic), 471
 - Duality, 41
 - Dual-trace oscilloscope, 512
 - Dynamic hazard, 453
 - Dynamic memory, refreshing, 291
 - Dynamic RAM (DRAM), 291
 - address coding of, 295
- E**
 - ECL (emitter-coupled logic), 471
 - Edge-sensitive cyclic behavior, 344
 - Edge-triggered *D* flip-flop, 189–191, 531
 - graphic symbol for, 191
 - hold time, 191
 - master, 189–190
 - setup time, 191
 - slave, 189–190
 - with three *SR* latches, 190–191
 - with two *D* latches and an inverter, 189–190
 - Electrically erasable PROM (EEPROM/E²PROM), 304
 - Electronic design automation (EDA), 65
 - Emitter-coupled logic (ECL), 493–495
 - basic circuit, 493
 - defined, 493
 - external wired connection of two OR outputs, 495
 - graphic symbol, 495
 - internal temperature- and voltage-compensated bias circuit, 493
 - internal wired connection of two OR outputs, 495
 - propagation delay, 494–495
 - Enable input, 288
 - Encoders, 150–152
 - octal-to-binary, truth table for, 150
 - priority, 151–152
 - endmodule (keyword), 109
 - Erasable PROM (EPROM), 304
 - Error detection scheme, parity bit as, 296
 - Error detection/correction, 296–299
 - Hamming code, 296–298, 299
 - single-error correction, double-error detection, 298–299
 - Error-correcting code, 296
 - Error-detecting code, 25
 - Essential hazards, 456–457
 - Event control operator, 208
 - Excess-3 code, 21–22
 - Excitation equations, flip-flops, 200
 - Excitation table, 229
 - Exclusive-NOR function (XNOR), 57
 - Exclusive-OR gate, 59
 - Exclusive-OR symbol (\oplus), 55
 - Exclusive-OR (XOR) function, 57, 101–102, 104
- F**
 - Fan-in, 64
 - Fan-out, 64, 473–474
 - Fast TTL family, 485
 - Fault simulation, 108
 - Feedback shift register, 537
 - Feedback-free continuous assignment, 403
 - Field, 37–38
 - Field-effect transistor (FET), 473, 495
 - Field-programmable gate array (FPGA), 65, 284, 311, 315, 343
 - design with, 315
 - logic block, 315
 - Xilinx FPGAs, 316
 - Xilinx Spartan II FPGAs, 323–327
 - Xilinx Spartan XL FPGAs, 322–323
 - Xilinx Virtex FPGAs, 327–329

- Field-programmable logic sequencer (FPLS), 313
 - Finite state machines, Mealy and Moore models of, 206–207
 - First-in, first-out register files (FIFOs), 320–321
 - Five-variable map, 81–83
 - Flash memory devices, 304
 - Flip-flops, 183–184, 188–195, 242
 - characteristic equations, 194
 - characteristic tables, 193–194
 - construction of, 188–189
 - defined, 183
 - direct inputs, 194–195
 - dynamic indicator, 191
 - edge-triggered *D* flip-flop, 189–191
 - input equations, 199–200
 - JK* flip-flops, 192
 - laboratory experiment, 530–532
 - D* latch, 530
 - edge-triggered flip-flop, 531
 - IC flip-flops, 531–532
 - master-slave flip-flop, 530
 - SR* latch, 530
 - operation of, 189
 - operations performed with, 192
 - as registers, 335
 - and signal transition, 189
 - symbols, 568–570
 - T* flip-flops, 192
 - timing of the response of, 191
 - Flow table, 420–422
 - defined, 420
 - examples of, 420
 - obtaining the logic diagram from, 422
 - primitive, 421
 - Flowcharts, 346
 - for loop, 340–341
 - forever loop, 340–341
 - Four-bit data-storage register, 244
 - Four-to-one-line multiplexers, 153
 - Four-variable map, 76–80
 - prime implicants, 79–80
 - FPGA (field-programmable gate array), 284
 - Full adder, 130, 131–133, 527
 - Function blocks, 315
- G**
- Gate array, 315
 - Gate instance, 110
 - Gate instantiation, 110
 - Gate-level minimization, 70–121
 - AND–OR–INVERT function, 96
 - implementation, 97–99
 - defined, 70
 - don't-care conditions, 86–88
 - exclusive-OR (XOR) function, 101–102
 - five-variable map, 81–83
 - four-variable map, 76–80
 - prime implicants, 79–80
 - gate delays, 110–113
 - hardware description language (HDL), 106–116
 - Karnaugh map (K-map), 70–71
 - map method, 70–71
 - multilevel NAND circuits, 92–93
 - NAND gate, 89–90
 - nondegenerate forms, 97
 - NOR gate, 93–96
 - odd function, 102–104
 - OR–AND–INVERT function, 96
 - implementation, 98–100
 - parity checker, 104–106
 - parity generation, 104–106
 - product-of-sums simplification, 83–86
 - three-variable map, 72–76
 - two-level implementation, 90–92
 - two-variable map, 71–72
 - Gate-level (structural) modeling, 159
 - Giga (G), 4
 - Gray code, 22–23
- H**
- Half adder, 130–131, 527
 - Hamming code, 296–298
 - modified, 299
 - using for data words, 298
 - Hardware algorithm, 346
 - Hardware description language (HDL), 65, 106–116, 159, 315
 - Boolean expressions, 113–114
 - defined, 106
 - design entry, 107
 - as documentation language, 107
 - fault simulation, 108
 - logic simulation, 107
 - module declaration, 108–109
 - register transfer level (RTL) in, 336–345
 - for registers and counters, 269–276
 - switch-level modeling, 505–508
 - transmission gate, 506–507
 - test bench, 107
 - timing verification, 107–108
 - user-defined primitives, 114–116
 - Hardware signal generators, 112
 - Hazards, 452–457
 - in combinational circuits, 452–454
 - defined, 452
 - detection of, 453
 - dynamic, 453
 - essential, 456–457
 - implementation with *SR* latches, 454–456
 - remedy for eliminating, 454
 - in sequential circuits, 454
 - static 0-hazard, 453
 - static 1-hazard, 453
 - Hexadecimal (base-16) number system, 3–4
 - Hexadecimal numbers, 8–9
 - High impedance, 159
 - High-impedance state, 156
 - High-speed TTL gate, 484–485
 - Huntington, E. V., 38
- I**
- IC digital logic families, 471
 - basic circuits in, 471
 - bipolar junction transistor (BJT), 473
 - data book, 471–472
 - field-effect transistor (FET), 473
 - NAND gates, 471–472
 - NOR gates, 471–472
 - special characteristics, 473–477
 - fan-out, 473–474
 - noise margin, 476–477
 - power dissipation, 474–475
 - propagation delay, 475–476
 - Identity element, 37
 - Implication table, 440–441
 - incompletely specified functions, 87
 - Information transfer, between registers, 335
 - initial** block, 218
 - Input equations, flip-flops, 199–200
 - Instantiation, 110, 160
 - Institute of Electronics and Electrical Engineers (IEEE), 65
 - integer** data type, 342
 - Integrated circuit RAM units, 291
 - Integrated circuits (ICs), 63–65, 471
 - computer-aided design, 64–65
 - digital logic families, 63–64
 - levels of integration, 63
 - Interconnect resources, 317–318
 - programmable, 319
 - Intra-assignment delay, 274
 - Inverse, 37
- J**
- JK* flip-flops, 192
 - analysis of clocked sequential circuits with, 204–206

- analysis with, 201–204
 - characteristic table, 193
 - Johnson counters, 268–269
 - Junction field-effect transistor (JFET), 495
- K**
- Karnaugh map (K-map), 70–71, 343
 - Keywords, 108–109
 - Kilo (k), 4
- L**
- Laboratory experiments, 511–558
 - adders and subtractors
 - (experiment 7), 527
 - adder-subtractor (four-bit), 528–529
 - full adder, 527
 - half adder, 527
 - magnitude comparator, 529–530
 - parallel adder, 528
 - asynchronous sequential circuits
 - (experiment 18), 553
 - binary and decimal numbers
 - (experiment 1), 516
 - BCD count, 517–518
 - binary count, 516–517
 - counts, 518
 - oscilloscope display, 517
 - output pattern, 517–518
 - binary multiplier (experiment 17), 549–553
 - block diagram, 549–550
 - checking, 552–553
 - control of registers, 550–552
 - datapath design, 552
 - design of control circuit, 552
 - multiplication example, 552
 - Boolean function simplification
 - (experiment 3), 520–522
 - Boolean functions in sum-of-minterms form, 522
 - complement, 522
 - gate ICs, 521
 - logic diagram, 521–522
 - clock-pulse generator (experiment 15), 545–547
 - circuit operation, 545–546
 - clock-pulse generator operation, 546–547
 - IC timer, 545
 - code converters (experiment 5), 524–526
 - Gray code to equivalent binary, 524
 - nine's complements, 525
 - seven-segment display, 525–526
 - combinational circuits (experiment 4), 522–524
 - decoder and truth table block diagram, 523–524
 - decoder implementation, 523–524
 - design example, 523
 - majority logic, 523
 - parity generator, 523
 - counters (experiment 10), 533–535
 - binary counter with parallel load, 534–535
 - decimal counter, 534
 - ripple counter, 534
 - synchronous counter, 534
 - digital logic gates (experiment 2), 519–520
 - NAND circuit, 520
 - propagation delay, 519–520
 - truth tables, 519
 - universal NAND gate, 520
 - waveforms, 519
 - digital logic trainers, 511–512
 - dual-trace oscilloscope, 512
 - flip-flops (experiment 8), 530–532
 - D latch, 530
 - edge-triggered flip-flop, 531
 - IC flip-flops, 531–532
 - master-slave flip-flop, 530
 - SR latch, 530
 - gate ICs needed for, 512
 - graphic symbols, 515
 - IC type 7493 ripple counter, 512
 - operation of, 512–515
 - integrated circuits required, 515
 - lamp handball (experiment 15), 541–545
 - circuit analysis, 544
 - counting the number of losses, 544
 - IC type 74194, 542
 - Lamp Ping-Pong™, 545
 - logic diagram, 542–544
 - playing the game, 544
 - logic breadboard suitable for performing, 511
 - medium-scale integration (MSI) circuits, 512
 - memory unit (experiment 14), 539–541
 - IC RAM, 539–540
 - memory expansion, 541
 - ROM simulator, 541
 - testing the RAM, 540–541
 - multiplexer design (experiment 6), 526–527
 - specifications, 527
 - parallel adder and accumulator (experiment 16), 547–549
 - block diagram, 547
 - carry circuit, 548
 - checking the circuit, 548
 - circuit operation, 549
 - control of register, 547
 - detailed diagram of circuit, 548
 - sequential circuits (experiment 9), 532–533
 - counter design, 533
 - state diagram, 533
 - up-down counter with enable, 533
 - serial addition (experiment 12), 538–539
 - serial adder, 539
 - serial adder-subtractor, 539
 - testing the adder, 539
 - shift registers (experiment 11), 535–538
 - bidirectional shift register, 537
 - bidirectional shift register with parallel load, 537–538
 - feedback shift register, 537
 - IC shift register, 535–536
 - ring counter, 537
 - small-scale integration (SSI) circuits, 512
 - Verilog HDI simulation experiments and rapid prototyping with FPGAs, 553
 - experiment 1, 554
 - experiment 2, 554–555
 - experiment 4, 555–556
 - experiment 5, 556
 - experiment 7, 556
 - experiment 8, 556
 - experiment 9, 557
 - experiment 10, 557
 - experiment 11, 557
 - experiment 13, 557–558
 - experiment 14, 558
 - experiment 16, 558
 - experiment 17, 558
 - Lamp handball (laboratory experiment), 541–545
 - circuit analysis, 544
 - counting the number of losses, 544
 - IC type 74194, 542
 - Lamp Ping-Pong™, 545
 - logic diagram, 542–544
 - playing the game, 544
 - Large-scale integration (LSI) devices, 63
 - Latches, 184–188
 - D latch (transparent latch), 187–188
 - reset state, 185
 - sensitivity of, 184
 - set state, 185

- Latches (*cont.*)
 - SR latch, 185–187
 - trigger, 188
 - Latch-free design, 403–404
 - Literals, 46
 - Load operation, registers, 244, 334
 - Logic circuits, *See* Digital systems
 - Logic diagram:
 - obtaining output Boolean functions from, 124
 - of three-bit binary counter, 234
 - Logic gates, 30–31
 - Logic operations, digital systems, 336
 - Logic operators, Verilog 2001 HDL, 339
 - Logic operators, for binary words, 338
 - Logic simulation, 107
 - Logic simulators, 122
 - Logic synthesis, 343–345
 - advantages to designer, 345
 - assign** statement, 343
 - tools, 343
 - Logical operators, Verilog 2001 HDL, 339
 - Loop statements, 340–341
 - Low-power Schottky TTL, 485
 - Low-power TTL gate, 484
- M**
- Magnetic disk, 290–291
 - Magnitude comparator, 143–145, 529–530
 - four-bit, 145
 - Mask programming, 303
 - Master-slave flip-flop, 530
 - Maximal compatibles, 444–445
 - Mealy FSM (Mealy machine), 206
 - Mealy model, 206–207
 - Mealy_Zero_Detector*, 215–216
 - Medium-scale integration (MSI)
 - circuits, 512
 - Medium-scale integration (MSI)
 - devices, 63
 - Mega (M), 4
 - Mem*, 288
 - Memory:
 - access time, 289
 - address, 286
 - architecture of, 285
 - communication between the environment and, 285
 - cycle time, 289
 - integrated circuit RAM units, 291
 - programmable logic device (PLD), 284
 - random-access (RAM), 284
 - sequential-access, 290
 - types of, 290–291
 - Memory cell, 291–292
 - Memory chip, control inputs to, 288
 - Memory cycle timing waveforms, 289–290
 - Memory decoding, 291–295
 - address multiplexing, 294–295
 - coincident decoding, 293–294
 - internal construction, 291–292
 - Memory depth, 288
 - Memory description in HDL, 288–289
 - Memory enable, 287, 289
 - Memory system, mode of access of, 290
 - Memory timing, 289
 - Memory units, 284–287
 - block diagram, 285–286
 - capacity of, 285
 - defined, 284–285
 - laboratory experiment, 539–541
 - IC RAM, 539–540
 - memory expansion, 541
 - ROM simulator, 541
 - testing the RAM, 540–541
 - operation of, 288
 - reliability of, 296
 - volatile, 291
 - words, 285, 287
- memword*, 288
- Merger diagram, 444
 - Metal-oxide semiconductor (MOS):
 - advantage of, 497
 - basic structure of, 495
 - channel, 495
 - depletion mode, 496
 - diffused channel, 496
 - drain, 495
 - enhancement mode, 496
 - gate, 495
 - graphic symbols, 496
 - n*-channel MOS, 496–497
 - p*-channel MOS, 496–497
 - source, 495–496
 - types of, 496
 - Metal-oxide-semiconductor field-effect transistor (MOSFET), 473
 - Module, 207
 - module ... endmodule** (keyword pair), 109
 - Module declaration, 108–110
 - Modules, 108–110, 217
 - Modulo-*N* counter, 265
 - Moore FSM (Moore machine), 206
 - Moore model, 206–207
 - MOS, *See* Metal-oxide semiconductor (MOS)
 - Multilevel NAND circuits, 92–93
 - Multiple-row method, 450–452
 - Multiplexers, 152–158, 313
 - Boolean function implementation, 154–156
 - data selector, 154
 - defined, 152
 - design example, 393–400
 - testing the ones counter, 400–401
 - design with, 390–401
 - laboratory experiment, 526–527
 - four-to-one-line, 153
 - graphics symbols for, 567
 - implementing a Boolean function with, 156
 - implementing a four-input function with, 157
 - input conditions, 393
 - quadruple two-to-one-line, 155
 - three-state gates, 156–158
 - two-to-one-line, 152–153, 153
- N**
- NAND gate, 89–90
 - n*-bit binary code, 17–18
 - Negation (–) operator, 338
 - negedge** (keyword), 209
 - Nets, 164
 - Noise, defined, 476
 - Noise margin, 64, 476–477
 - Nonblocking assignments, 209–210, 337–338
 - Noncritical race, 422
 - Nondegenerate forms, 97
 - Nonvolatile memory, 291
 - NOR gate, 93–96
 - NOT operation, 29
 - npn* type, bipolar transistor, 477–478
 - silicon transistor parameters, 479
 - n*-to-*m*-line decoders, 146
 - Number-base conversions, 5–7
- O**
- Octal number system, 4
 - Octal numbers, conversion to hexadecimal, 9
 - Octal-to-binary encoder, truth table for, 150
 - Odd function, 102–104
 - One-hot assignment, 224–225
 - One-hot design, 380–382
 - Open Verilog International (OVI), 108
 - Open-collector output gate, 485–488
 - AND–OR–INVERT function, 487
 - applications, 486
 - forming a common bus line, 487–488
 - NAND gate, 485
 - wired-AND, 487

- Operator precedence, 43–44
- OR gate, conventional and array logic diagrams for, 285
- OR operation, 29
- Output equations, flip-flops, 200
- Overflow, 138–139
- P**
- PAL, *See* Programmable array logic (PAL)
- Parallel adder, 528
- laboratory experiment, 547–549
- block diagram, 547
- carry circuit, 548
- checking the circuit, 548
- circuit operation, 549
- control of register, 547
- detailed diagram of circuit, 548
- Parallel load:
- bidirectional shift register with, 537–538
- binary counters with, 534–535
- Clear input, 262–264
- CLK input, 264
- Count input, 264
- Load input, 264
- registers with, 244–245
- Parallel multiplier, behavioral description of, 388–390
- Parallel-load control, shift registers, 251
- parameter (keyword), 213
- Parity bit, 25
- as error detection scheme, 296
- Parity checker, 104–106
- Parity generation, 104–106
- Parity generator, combinational circuits, 523
- PIP-based interconnection, architecture of, 319–320
- PLA, *See* Programmable logic array (PLA)
- PLD, *See* Programmable logic device (PLD)
- pnp* type, bipolar transistor, 477–478
- posedge (keyword), 209
- Positive-edge-triggered *D* flip-flop, 194–195
- Power dissipation, 64, 474–475
- Powers of two (table), 5
- Predefined primitives, 110
- Preset inputs, flip-flops, 194–195
- Prime implicants, 79–80
- Primitive flow table, 421, 457–458
- Primitive gates, 110
- Primitives, 110
- Priority encoders, 151–152
- four-input, 152
- maps for, 151
- truth table for, 151
- Procedural assignments, 337
- Product of sums, 54
- expression, 95
- simplification, 83–86
- Programmable array logic (PAL), 284–285, 309–311
- commercial, 309
- defined, 309
- designing with, 309, 311
- fuse map for, 311
- programming table, 309–311
- Programmable logic array (PLA), 284, 305–308
- defined, 305
- designing a digital system with, 307
- fuse map of, 306, 308
- implementing a combinational circuit with, 307–308
- internal logic of, 305
- programming table:
- generation of, 308
- sections of, 306
- size of, 307
- Programmable logic device (PLD), 65, 284–285, 343
- design with, 315
- Programmable read-only memory (PROM), 303–304
- Programming, 284–285
- Propagation delay, 64, 475–476
- digital logic gates (laboratory experiment), 519–520
- emitter-coupled logic (ECL), 494–495
- IC digital logic families, 475–476
- transistor–transistor logic (TTL), 484
- Q**
- Quadruple two-to-one-line multiplexers, 155
- Qualifying symbols, 562–564
- Qualitative analysis, 480
- Quantitative analysis, 480
- R**
- Race conditions, 422–424
- critical race, 422–423
- avoiding, 447
- examples of, 423
- cycles, 423–424
- noncritical race, 422
- Race-free design, 401–403
- software race conditions, 403
- Race-free state assignment, 446–452
- four-row flow-table example, 449–450
- multiple-row method, 450–452
- three-row flow-table example, 447–449
- Radix, 3–4, 10–11
- Radix complement, 10–11
- RAM, *See* Random-access memory (RAM)
- Random-access memory (RAM), 284–291
- commercial, word capacity of, 292
- memory description in HDL, 288–289
- memory, types of, 290–291
- symbol for, 574
- timing waveforms, 289–290
- write and read operations, 287–288
- Read cycle, 289
- Read input, 285
- Read operation, 284
- Read-only memory (ROM), 284, 299–305
- block diagram, 299–300
- combinational circuit
- implementation, 302
- combinational programmable logic device (PLD), 304–305
- defined, 299
- electrically erasable PROM (EEPROM/E²PROM), 304
- erasable PROM (EPROM), 304
- flash memories, 304
- internal binary storage of, 300
- internal operation of, 302
- mask programming, 303
- number of words in, 299
- programmable read-only memory (PROM), 303–304
- programming, 300–301
- truth table, 301
- types of, 303–304
- Read/Write input, 288
- Read/write signals, 289
- Rectangular-shape symbols, 559–561
- Reduction operators, 338
- reg variable, 342
- Register operations, 334
- Register symbols, 570–572
- Register transfer, 26–28
- Register transfer level (RTL), 2
- algorithmic state machines (ASMs), 345–352
- design example, 352–361
- binary multiplier:
- control state diagram for, 376
- HDL description of, 382–389

- Register transfer level (RTL) (*cont.*)
 continuous assignments, 337
 control logic, 376–382
 design at, 334–414
 digital system represented at, 334
 in HDL, 336–345
 HDL operators, 338–340
 logic synthesis, 343–345
 loop statements, 340–341
 latch-free design, 403–404
 multiplexers, design with, 390–401
 notation, 334–335
 procedural assignments, 337–338
 race-free design, 401–403
 sequential binary multiplier, 370–376
- Register transfer operations, 334, 336
- Registers, 26, 242–253, 334. *See also*
 Register transfer level (RTL)
 defined, 242, 335
 four-bit data-storage register, 244
 HDL for, 269–276
 ripple counter, 274–276
 shift register, 269–273
 synchronous counter, 273–274
 loading, 244
 with parallel load, 244–245
 shift registers, 245–253
 defined, 245
 serial addition, 248–250
 serial input, 246
 serial output, 246
 serial transfer, 246–248
 simple, 245–246
 universal, 250–253
 types of, 242–243
 updating, 244
- Relational operators, Verilog 2001
 HDL, 339
- repeat loop, 340
- Reset state, latches, 185
- Ring counters, 267–268, 537
- Ripple counters, 253–258, 534
 BCD, 256–258
 binary, 253–256
 defined, 253, 256
 HDL for, 274–276
- ROM (read-only memory),
See Read-only memory (ROM)
- RTL digital logic family:
 analysis of, 481
 fan-out, 481–482
 NOR gate, 481
- RTL (resistor-transistor logic), 471
- S**
- Schematic capture, 65
- Schematic entry, 65
- Schottky transistor, defined, 489
- Schottky TTL gate, 484–485, 489–491
 symbol for Schottky
 transistors/diodes, 490
- Scratchpad memories, 321
- Sensitivity list, 208
- Sequence detector:
 maps for, 228
 state diagram for, 227
 state table for, 228
- Sequential binary multiplier, 370–376
 ASMD chart, 373–376
 register configuration, 372–373
 state diagram, 533
- Sequential circuits, 182–184, 415–470
 asynchronous, 183
 block diagram, 182
 hazards in, 454
 laboratory experiment, 532–533
 counter design, 533
 state diagram, 533
 up-down counter with enable, 533
 synchronous, 183
- Sequential (or simple) programmable
 logic device (SPLD), 311, 313
- Sequential programmable devices,
 311–329
 complex programmable logic device
 (CPLD), 311, 313–315
 design with, 315
 configurable logic block (CLB), 317
 distributed RAM, 317
 enhancements, 320–321
 field-programmable gate array
 (FPGA), 65, 284, 311, 315
 design with, 315
 logic block, 315
 Xilinx FPGAs, 316
 Xilinx Spartan II FPGAs, 323–327
 Xilinx Spartan XL FPGAs, 322–323
 Xilinx Virtex FPGAs, 327–329
- interconnect resources, 317–318
- I/O block (IOB), 320
- sequential (or simple) programmable
 logic device (SPLD), 311, 313
- Xilinx:
 basic architecture, 316–317
 FPGAs, 316
- Sequential-access memory, 290
- Serial adder, 248, 539
 second form of, 250
 state table for, 250
- Serial addition, 248–250
 laboratory experiment, 538–539
 serial adder, 539
 serial adder-subtractor, 539
 testing the adder, 539
- Serial bit stream, 227
- Serial input, 246
- Serial output, 246
- Serial transfer, 246–248
- Set, 36
- Set state, latches, 185
- Shannon, C. E., 38
- Shared-row method, 451
- Shift operation, registers, 334
- Shift operators, Verilog 2001 HDL, 339
- Shift register, HDL for, 269–273
- Shift registers, 245–253, 321
 bidirectional, 251
 clear control, 251
 clock input, 251
 defined, 245
 laboratory experiment, 535–538
 bidirectional shift register, 537–538
 bidirectional shift register with
 parallel load, 537–538
 feedback shift register, 537
 IC shift register, 535–536
 ring counter, 537
 parallel-load control, 251
 serial addition, 248–250
 serial input, 246
 serial output, 246
 serial transfer, 246–248
 shift-left control, 251
 shift-right control, 251
 simple, 245–246
 unidirectional, 251
 universal, 250–253
- Shift-left control, shift registers, 251
- Shift-right control, shift registers, 251
- Signed binary numbers, 14–17
 arithmetic addition, 16
 arithmetic subtraction, 17
- Signed-complement system, 14
- Signed-magnitude convention, 14
- Simple shift registers, 245–246
- Simple_Circuit_prop_delay*, 111–112
- Single-error correction, double-error
 detection, 298–299
- Single-pass behavior, 207
- Small-scale integration (SSI) circuits, 512
- Small-scale integration (SSI) devices, 63
- Software race conditions, 403
- Spartan chips, 320–321
- Spartan device families, comparison
 chart, 324
- Spartan devices, 317
- Spartan II FPGAs, 323–327
 device attributes (table), 324
- Spartan XL FPGAs, 322–323
 architecture of, 323
 device attributes (table), 323

- SPLD, *See* Sequential (or simple) programmable logic device (SPLD)
- SR latch, 185–187
- SRAM, *See* Static RAM (SRAM)
- Stable circuits, 424–425
- Standard forms:
- Boolean algebra, 48–55
 - defined, 54
 - expression of a Boolean function in, 55
 - product of sums, 54
 - sum of products, 54–55
- Standard graphic symbols, 559–576
- combinational element symbols, 566–568
 - counter symbols, 572–574
 - dependency notation, 564–566
 - flip-flop symbols, 568–570
 - qualifying symbols, 562–564
 - RAM symbol, 574
 - rectangular-shape symbols, 559–561
 - register symbols, 570–572
- State assignment, 224–225
- State diagram, 199, 213–217
- compared to a state table, 198
 - reducing, 223–224
 - for sequence detector, 227
- State equations, 196–197
- Boolean expressions for, 197
 - defined, 196–197
- State machine, defined, 346
- State reduction, 220–223
- State table, 197–198
- binary form of, 225
 - compared to a state diagram, 198
 - and JK flip-flop inputs, 231
 - reducing, 222–223
 - sections, 198
 - for sequence detector, 228
 - for three-bit binary counter, 231–233
- State tables, reduction of, 439–441
- Static 0-hazard, 453
- Static 1-hazard, 453
- Static RAM (SRAM), 291
- Storage elements:
- defined, 184
 - flip-flops, 188–195
 - latches, 184–188
- Sum of products, 54–55
- Switch-level modeling, 505–508
- transmission gate, 506–507
- Switch matrices, and CLB architecture, 317–319
- Switching algebra, 38
- Synchronous counters, 258–264, 534
- BCD counter, 260–262
 - state table for, 260–262
- binary counter, 258–260
- four-bit, 259
- binary counter with parallel load, 262–265
- Clear input, 262–264
 - CLK input, 264
 - Count input, 264
 - Load input, 264
- defined, 253
- HDL for, 273–274
- up-down binary counter, 260
 - four-bit, 261
- Synchronous RAM (SelectRAM), 320–321
- Synchronous sequential circuits, 183, 225
- Synchronous sequential logic, 182–241
- clocked sequential circuits, analysis of, 195–207
 - design procedure, 225–234
 - sequential circuits, 182–184
 - state assignment, 224–225
 - state reduction, 220–223
 - storage elements:
 - defined, 184
 - flip-flops, 188–195
 - latches, 184–188
 - synthesizable HDL models of sequential circuits, 207–220
- Syndrome, 296
- Synthesis, 226
- Synthesis tools, 315
- Synthesizable HDL models of sequential circuits, 207–220
- behavioral modeling, 207–210
 - clocked sequential circuits, structural description of, 217–220
 - flip-flops and latches, 210–213
 - state diagram, 199
- System primitives, 114
- T**
- T flip-flops, 192
- analysis of clocked sequential circuits with, 204–206
 - analysis with, 204–206
 - characteristic table, 193–194
 - conditions, 194
- t*, Simple_Circuit_prop_delay, 112
- Tape unit, 290
- Tera (T), 4
- Test access port (TAP) controller, 320
- Test bench, 107, 111
- Test bench module, 218
- Three-bit binary counter:
- logic diagram of, 234
 - maps for, 234
 - state diagram of, 233
 - state table for, 231–233
- Three-state buffer gate, graphic symbol for, 157
- Three-state gates, 156–158, 491–493
- buffer gate, graphic symbol of, 491–492
 - bus, creation of, 493
 - inverter, 491–492
 - output enable delay compared to output disable delay, 493
 - output states, 491
- Three-to-eight-line decoder, 146
- truth table for, 147
- Three-variable map, 72–76
- Time units, 110
- Time-delay devices, 183
- Timing verification, 107–108
- Timing waveforms, 289–290
- Top-down design, 161
- Total state, 419
- Totem-pole output, 488–489
- defined, 488
 - wired-logic connection, 489
- Transfer function, 57
- Transfer operations, digital systems, 336
- Transistors, 1
- Transistor–transistor logic (TTL):
- advanced low-power Schottky TTL gate, 485
 - characteristics (table), 484
 - defined, 471
 - fast TTL family, 485
 - high-speed TTL gate, 484–485
 - low-power Schottky TTL, 485
 - low-power TTL gate, 484
 - open-collector output gate, 485–488
 - original, 484
 - propagation delay, 484
 - Schottky TTL gate, 484–485, 489–491
 - standard, 484
 - three-state gate, 491–493
 - totem-pole output, 488–489
 - TTL gate, operation of, 471
- Transition diagram, 447
- Transition equation, *See* State equations
- Transition table, 225, 417–420, *See* State table
- of asynchronous sequential circuits, 419–420
- Transparent latch, 187–188
- Trigger, latches, 188
- Truth tables, 29
- TTL, *See* Transistor–transistor logic (TTL)
- 2421 code, 21–22
- Two-level implementation, 90–92
- Two-to-four-line decoder, with enable input, 147–148
- Two-to-one-line multiplexers, 152–153, 153

Two-valued Boolean algebra,
39–41

Two-variable map, 71–72

U

UDPs, *See* User-defined primitives
(UDPs)

Unidirectional shift registers, 251

Universal NAND gate, 520

Universal shift registers, 250–253
four-bit, 252

Unknown value, 159

Unsigned binary numbers, 14

Unstable circuits, 424–425

Unused states, 224

counters with, 265–266

Updating a register, 244

User-defined primitives (UDPs), 114–116

V

Vectors, 160

Verilog HDL, 108, 159, 207, 209, 315

memory description in, 288

operators, 165, 338–340

switch-level modeling, 505–508

transmission gate, 506–507

Very large-scale integration (VLSI)

devices, 63–65

VHDL, 108, 315

Virtex FPGAs, 327–329

Volatile memory units, 291

W

Waveforms, 519

Weighted codes, 21

while loop, 340–342

Wired logic, 96

Word length, 288

Word locations, 290

Words, 285, 287

Write input, 285

Write operation, 284

X

Xilinx:

basic architecture, 316–317

FPGAs, 316

Spartan II FPGAs, 323–327

Spartan XL FPGAs, 322–323

Virtex FPGAs, 327–329

XNOR function, 57

XOR function, 57