

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 complement, 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
- 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 operations, digital systems, 336
- 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