0, 23. See also LOW, OFF	floating-point, 252–255	ALU decoder, 374–376
1, 23. See also HIGH, ON	overflow. See Overflow	ALU decoder truth table, 376
74xx series logic, 515–516	two's complement, 15, 240	ALUControl, 370
parts,	underflow. See Underflow	ALUOp, 374–375
2:1 Mux (74157), 518	unsigned binary, 15	ALUOut, 383–385
3:8 Decoder (74138), 518	Address, 485–490	ALUResult, 370–371
4:1 Mux (74153), 518	physical, 485	AMAT. See Average memory access time
AND (7408), 517	translation, 486–489	Amdahl, Gene, 468
AND3 (7411), 517	virtual, 485–490	Amdahl's Law, 468
AND4 (7421), 517	word alignment, 298	Anodes, 27–28
Counter (74161, 74163), 518	Addressing modes, 327–329	and immediate (and i), 306, 346-347
FLOP (7474), 515–517	base, 327	AND gate, 20–22, 32–33
NAND (7400), 517	immediate, 327	Application-specific integrated circuits
NOR (7402), 517	MIPS, 327–329	(ASICs), 523
NOT (7404), 515	PC-relative, 327–328	Architectural state, 363–364
OR (7432), 517	pseudo-direct, 328–329	Architecture. See Instruction Set
XOR (7486), 517	register-only, 327	Architecture
Register (74377), 518	Advanced microarchitecture, 435–447	Arithmetic, 233–249, 305–308, 515.
Tristate buffer (74244), 518	branch prediction. See Branch	See also Adders, Addition,
schematics of, 517–518	prediction	Comparator, Divider,
•	deep pipelines. See Deep pipelines	Multiplier
	multiprocessors. See Multiprocessors	adders. See Adders
A	multithreading. See Multithreading	addition. See Addition
	out-of-order processor.	ALU. See Arithmetic/logical unit
	See Out-of-order processor	circuits, 233–248
add <b>, 29</b> 1	register renaming. See Register	comparators. See Comparators
Adders, 233–240	renaming	divider. See Divider
carry-lookahead. See Carry-	single instruction multiple data. See	division. See Division
lookahead adder	Single instruction multiple	fixed-point, 249
carry-propagate (CPA). See Carry-	data (SIMD) units	floating-point, 252-255
propagate adder	superscalar processor. See	logical instructions, 305-308
prefix. See Prefix adder	Superscalar processor	multiplier. See Multiplier
ripple-carry. See Ripple-carry adder	vector processor. See Single instruc-	packed, 445
add immediate (addi), 327, 378	tion multiple data (SIMD)	rotators. See Rotators
add immediate unsigned (addiu), 552	units	shifters. See Shifters
add unsigned (addu), 554	Alignment. See Word alignment	signed and unsigned, 338-339
Addition, 14-15, 233-240, 291	ALU. See Arithmetic/logical unit	subtraction. See Subtraction

242-244, 515 32-bit, 244 adder. See Adders ALUQ, 374-376 ALUQut, 383-385 ALUResult, 370-371 ALUQut, 383-385 comparators control, 242 subtractor. See Subtractor Arrays, 314-318 accessing, 315-317 bytes and characters, 316-318 pytes and characters, 316-318 point point accessing, 315-317 point point accessing, 315-317 point point big-Endian, 172, 296-297 pinary numbers, 9-11. See also point Ascemble directives, 333 pytes producted decimal, 252 conversion. See Number conversion fixed point, 249-250 floating-point. See Floating-point numbers signed, 15-19 pushing, 67-69 push	Arithmetic (Continued)	Base 16 number representations.	sum-of-products (SOP) canonical
Arithmetic/logical unit (ALU), 242-244, 515 32-bit, 244 adder. See Adders ALUOp, 374-376 ALUResult, 370-371 ALUResult, 370-371 ALUResult, 370-371 ALUResult, 370-371 ALUResult, 370-371 Base addressing, 327 Behavioral modeling, 171-185 Benchmarks, 367 SPEC2000, 398-399 Biased numbers, 41. See also Floating point accessing, 315-317 bytes and characters, 316-318 bper and characters, 316-318 breach, 385-385 memory. See Memory RAM, 265 ASCII (American Standard Code for Information Interchange) codes, 317 rable of, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assemble registers HIDI for, 192 Axioms. See Boolean axioms  B  B  B  B  B  B  B  B  B  B  B  B  B	subtractor. See Subtractor	See Hexadecimal numbers	form, 54–55
242-244, 315 32-bit, 244 adder. See Adders ALUQ, 374-376 ALUQut, 383-385 ALUResult, 370-371 ALUQut, 383-385 comparators control, 242 subtractor. See Subtractor Arrays, 314-318 accessing, 315-317 bytes and characters, 316-318 FPGA, See Field programmable gate array logic. See Logic arrays memory, See Memory RAM, 265 RSOM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language memory access time (AMAT), 467-468 B  B  B  B  B  B  B  B  B  B  B  B  B	underflow. See Addition, Underflow	Block,	
adder. See Adders ALUOp, 374-376 ALUResult, 370-371 ALUOut, 383-385 comparator. See Comparators control, 242 subtractor. See Subtractor Arrays, 314-318 accessing, 315-317 bytes and characters, 316-318 plogic. See Logic arrays memory. See Memory RAM, 265 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language, MIPS. See MIPS Assembler directives, 333 ASICs. See Application-specific integrated circuits Asynchronous crestrable registers HDL for, 192 Axioms. See Boolean axioms  B  Babbage, Charles, 7-8, 26 Base address, 295-296 Base register, 302, 343, 347 Base 2 number representations. See Bumber representations. See Bumber representations. See Buneber representations. See Dolean axioms, 57 equation simplification, 61-62 theorems, 57-60 Boolean axioms, 57 Boolean axioms, 57 Boolean exioms, 58 Boolean axioms, 57 Boolean exioms, 58 Boolean exioms, 57 Boolean exioms, 58 Boolean exioms, 57 Boolean exioms, 58 Boolean equations, 54-56 Boolean axioms, 57 Boolean exioms, 57 Boolean exioms, 58 Boolean exioms, 57 Boolean exioms, 57 Boolean exioms, 58 Boolean equations, 54-56 Boolean e	Arithmetic/logical unit (ALU),	digital building. See Digital building	Boolean theorems, 57-60
adder. See Adders ALUOp, 374-376 ALUOpt, 374-376 ALUOpt, 374-376 ALUOpt, 373-371 Base addressing, 327 Baudot, Jean-Maurice-Emile, 317 Comparator. See Comparators control, 242 Subtractor. See Subtractor Arrays, 314-318 Accessing, 313-317 Dytes and characters, 316-318 FPGA, See Field programmable gate array memory. See Memory RAM, 265 ROM, 266 ROM, 269 Romed decimal, 252 conversion. See Number conversion fixed point, 249-250 floating-point. See Floating-point numbers signed, 15-19 sign/magnitude. See Sign/ magnitude numbers two's complement numbers unsigned, 9-15 Binary to decimal conversion, 12 Binary to hexadecimal conversion, 12 Binary to hexad	242–244, 515	blocks	DeMorgan's, 59
ALUOp, 374–376 ALUResult, 370–371 ALUOup, 383–385 comparators See Comparators control, 242 subtractor. See Subtractor Arrays, 314–318 accessing, 315–317 bytes and characters, 316–318 BFCGA, See Field programmable gate array BPCGA, See Field programmable gate array memory. See Memory RAM, 265 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembler directives, 333 ASICs. See Application-specific integrated circuits from the point problement numbers spin-date decimal, 252 binary to decinal conversion, 10–11 linary to bexadecimal conversion, 12 linary to bexadecimal conversion, 12 linary to bexadecimal conversion, 12 linary t	32-bit, 244	in code,	complement, <b>58</b> , <b>59</b>
ALUOp, 374–376 ALUOp, 374–376 ALUOut, 383–385 comparator. See Comparators control, 242 subtractor. See Subtractor Arrays, 314–318 accessing, 315–317 bytes and characters, 316–318 PFCA, See Field programmable gate array logic. See Logic arrays memory. See Memory RAM, 265 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 ASsembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS B B B B B B B B B B B B B B B B B B B	adder. See Adders	else block, 311	consensus, 60
ALUResult, 370–371 ALUResult, 370–371 ALUCut, 383–385 comparator. See Comparators control, 242 subtractor. See Subtractor Arrays, 314–318 accessing, 315–317 bytes and characters, 316–318 PPCA, See Field programmable gate array logic. See Logic arrays memory, See Memory RAM, 265 RSPECLOOR, 387–395 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language Associativity, 58–59 Average memory access time (AMAT), Asynchronous inputs, 144 Asynchronous circuits, 116–117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  B  Babbage, Charles, 7–8, 26 Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Einary numbers Base 8 number representations. See Einary numbers See Otal numbers See Quation simplification, 61–62 theorems, 57–60 Boolean axioms, 57 Base 8 number representations. See Einary numbers See Otal n	ALUOp, 374–376		covering, 58
ALUOur, 383–385 comparators. See Comparators control, 242 subtractor. See Subtractor Arrays, 314–318 accessing, 315–317 bytes and characters, 316–318 PFCA, See Field programmable gate array indigic. See Logic arrays memory. See Memory RAM, 266 RSCII (American Standard Code for Information Interchange) codes, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language Associativity, 38–59 Average memory access time (AMAT), 467–468 Asynchronous circuits, 116–117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers See Octal numbers See Binary numbers See Octal numb	ALUResult, 370–371		combining, 58
comparator. See Comparators control, 242 subtractor. See Subtractor See Subtracto		<u> </u>	1.5
control, 242 subtractor. See Subtractor Arrays, 314–318 accessing, 315–317 bytes and characters, 316–318 FPGA, See Field programmable gate array logic. See Logic arrays memory. See Memory RAM, 265 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS Asynchronous circuits, 116–117 Asynchronous circuits, 116–117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Babe 2e number representations. See Binary numbers See Octal num			calculating address, 309
subtractor. See Subtractor Arrays, 314–318 accessing, 315–317 bytes and characters, 316–318 FPGA, See Field programmable gate array logic. See Logic arrays memory, See Memory RAM, 265 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASSEMBLY language, MIPS. See MIPS assembly language, MIPS. See MIPS assembly language, MIPS. See MIPS assembly language MIPS. See MIPS assembly language MIPS. See Sign/ Asynchronous inputs, 144 Asynchronous inputs, 146 Asynchronous inputs, 146 Asynchronous inputs, 146 Asynchronous resettable registers HDL for, 192 Bit cells, 258 Bit swizzling, 182 Bit itsele sperators, 171–174 Boole, George, 8 Bit swizzling, 182 Bit itsele sperators, 171–174 Boole, George, 8 Boolean algebra, 56–62 axioms, 57 equation simplification, 61–62 theorems, 57–60 Boolean acutions, 54–56 Base engister, 302, 343, 347 Base 2 number representations. See Binary numbers Base 8 number representations. See Binary numbers See Octal numbers See Octal numbers See Octal numbers Signed, 15–19 Signe			
Arrays, 314–318     accessing, 315–317     bytes and characters, 316–318     FPGA, See Field programmable gate array     array     ASCII, 317     binary coded decimal, 252     ROM, 265     ROM, 266     ASCII (American Standard Code for Information Interchange) codes, 317     Assembler directives, 333     ASICs. See Application-specific integrated circuits     Assembly language, MIPS. See MIPS     Assembly language, MIPS. See MIPS     Assembly language     Associativity, 58–59     Average memory access time (AMAT), 467–468     Asynchronous circuits, 116–117     Asynchronous inputs, 144     Asynchronous resettable registers     HDL for, 192     Axioms. See Boolean axioms  B  B  B  B  B  B  B  B  B  B  B  B  B	subtractor. See Subtractor	SPEC2000, 398-399	prediction, 437–438
accessing, 315-317 bytes and characters, 316-318 FPGA, See Field programmable gate array logic. See Logic arrays memory. See Memory RAM, 265 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language Assembly language Assembly language Assembly language Assembly language Assembly language Asserable memory access time (AMAT), 467-468 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Babbage, Charles, 7-8, 26 Babbage, Charles, 7-8, 26 Babbage, Charles, 7-8, 26 Base address, 295-296 Base address, 295-296 Base address, 295-296 Base 8 number representations. See Binary numbers Signed, 19-1 Babbage, Charles, 7-8, 26 Base 8 number representations. See Binary numbers Signed, 9-15 Binary to decimal conversion, 12 Birty 472 Babbage, Charles, 7-8, 26 Base 8 number representations. See Binary numbers See Octal numbers Signed, 9-15 Birty to decimal conversion, 12 Birty 482-483 Least significant, 13-14 mors significant, 13-14 mors significant, 13-14 Boolean axioms, 57 Babe 8 number representations. See Binary numbers Signed, 15-19	Arrays, 314–318		
bytes and characters, 316–318 FPGA, See Field programmable gate array logic, See Logic arrays memory. See Memory RAM, 265 ROM, 266 ASCII, 317 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language, MIPS. See MIPS Associativity, 58–59 Average memory access time (AMAT), 47–446 Asynchronous circuits, 116–117 Asynchronous circuits, 116–117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Bababage, Charles, 7–8, 26 Bababage, Charles, 7–8, 26 Base address, 295–296 Base address, 295–296 Base 2 number representations. See Binary numbers See Voctal numbers See Conversion. AscII, 317 Astribmetic Arithmetic Binary numbers Binary numbers Binary mumbers Binary mumbers Binary mumbers See Olal numbers Dinary coded decimal, 2.52 conversion ASCII, 317 Binary to decimal conversion floating-point. See Ploating-point numbers signed, 15–19 subble, 59 Bareadboards, 532–53 Bubble, 59 subble, 59 See Als	accessing, 315–317	_	
FPGA, See Field programmable gate array	9-	-	
Arithmetic logic. See Logic arrays memory. See Memory binary coded decimal, 2.52 conversion. See Number Codes, 317 codes, 317 signed, 15-19 signed, 15-19 signed, 15-19 sasembly language, MIPS. See MIPS assembly language unsigned, 9-15 binary to decimal conversion, 20 sayshcronous circuits, 116-117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  B b b b b c spins of the string of	•		* · · · · · · · · · · · · · · · · · · ·
logic. See Logic arrays memory. See Memory binary coded decimal, 252 coversion. See Number conversion. See Number conversion. See Number conversion. See Number conversion. See Note of Information Interchange) codes, 317 table of, 317 signed, 15–19 signed, 15–19 assembler directives, 333 sign/magnitude. See Sign/magnitude numbers assembly language, MIPS. See MIPS assembly language, MIPS. See MIPS assembly language assembly language assembly language with the seed assembly language assembly language with the seed assembly to the seat assembly language with the seed assembly to the seat assembly to the seed assembly to the seat assembly language with the seed assembly to the seat assembly the seed assembly to the seat assembly to the seat assembly to the seed assembly the seed a			
memory. See Memory RAM, 265  ROM, 266  ASCII (American Standard Code for Information Interchange) codes, 317  table of, 317  Assembler directives, 333  ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language, MIPS. See MIPS Assembly language  Associativity, \$8-59  Asynchronous circuits, 116–117  Asynchronous ricruits, 116–117  Asynchronous resettable registers  HDL for, 192  Axioms. See Boolean axioms  B  B  B  B  B  B  B  B  B  B  B  B  B	•		
RAM, 265 ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 Assembler directives, 333 ASIGs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language assembly langu			
ROM, 266 ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 table of, 317 Assembler directives, 333 ASIGs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language Associativity, 58–59 Average memory access time (AMAT), 467–468 Asynchronous circuits, 116–117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Bubble, 59 pushing, 67–69 Buffer, 20 tristate, 70–71 "Bugs," 169 Bus, 52 tristate, 71 Bypassing, 408 Bytes, 13–14 Bytes addressable memory, 295–297 Byte order, 296–297 Byte order, 296–297 Byte order, 296–297 Little-Endian, 296–297 Little-Endian, 296–297 Little-Endian, 296–297  C programming language, 290 overflows, 339 strings, 318 Caches, 468–484. See also Memory accessing, 472–473, 476–477, 479 Babbage, Charles, 7–8, 26 Base address, 295–296 Base a number representations. See Binary numbers Boolean axioms, 57 Base 8 number representations. See Binary numbers Boolean axioms, 57 Boolean axioms, 57 Boolean equations simplification, 61–62 theorems, 57–60 block size, 476–477 blocks, 469–470 data placement, 469–470			
ASCII (American Standard Code for Information Interchange) codes, 317 table of, 317 signed, 15–19 signed, 15–19  Assembler directives, 333 sign/magnitude. See Sign/ magnitude numbers tristate, 70–71 subgo, 52 troops assembly language, MIPS. See MIPS assembly language unsigned, 9–15 subgrated contains the formulation of the following signs of			
for Information Interchange) codes, 317 numbers in the codes, 317 table of, 317 signed, 15–19 sus, 52 tristate, 70–71 stable of, 317 signed, 15–19 signed, 15–19 sus, 52 tristate, 71 su		fixed point, 249–250	
codes, 317 table of, 317 signed, 15–19 Assembler directives, 333 ASICs. See Application-specific integrated circuits Assembly language, MIPS. See MIPS assembly language Associativity, 58–59 Average memory access time (AMAT), 467–468 Asynchronous circuits, 116–117 Asynchronous inputs, 144 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Birt cells, 258 Bit swizzling, 182 Bit wise operators, 171–174 Boole, George, 8 Babbage, Charles, 7–8, 26 Babbage, Charles, 7–8, 26 Babbage, Charles, 7–8, 26 Babe acddress, 295–296 Base address, 295–296 Base address, 295–296 Base 8 number representations. See Binary numbers Base 8 number representations. See Octal numbers Sign, 15–19 Sign, 15–19 Sign, 15–19 Sign, 16 Use, 478–479 Valid, 472 Boolean equations, 54–56 See Octal numbers Sign, 15–19 Base address, 295–297 Buss 8 number representations. See Octal numbers Sign/aganitude. See Sign/ Base address, 295–297 Buss 8 number representations. See Octal numbers Sign, 15–19 Buss 8 sign/magnitude numbers sign, 45–19 Buss sign/magnitude. See Sign/ Bagnitude. See Sign/ Bagnagnitude numbers two's complement. See Two's complement numbers Bius, 52 tristate, 71 Bypassing, 408 Bytes, 13–14 Byte-addressable memory, 295–297 Byte order, 296–297 Bityte order, 296–297 Little-Endian, 296–297 Little-Endian, 296–297  C programming language, 290 overflows, 339 strings, 318 Caches, 468–484. See also Memory accessing, 472–473, 476–477, 479 advanced design, 479–483 associativity, 469, 474–475, 478–479 blocks ice, 476–477 blocks, 469–470, 476 capacity, 468–470 data placement, 469–470			
table of, 317  Assembler directives, 333  ASICs. See Application-specific integrated circuits  Assembly language, MIPS. See MIPS  Assembly language, MIPS. See MIPS  Assembly language  Associativity, 58–59  Average memory access time (AMAT), 467–468  Asynchronous circuits, 116–117  Asynchronous resettable registers  HDL for, 192  Axioms. See Boolean axioms  Bell Bell Bell Bell Bell Bell Bell Bel		0.1	
Assembler directives, 333  ASICs. See Application-specific integrated circuits  Assembly language, MIPS. See MIPS assembly language  Associativity, 58–59  Average memory access time (AMAT), 467–468  Asynchronous circuits, 116–117  Asynchronous inputs, 144  Asynchronous resettable registers  HDL for, 192  Axioms. See Boolean axioms  B  B  B  B  B  B  B  B  B  B  B  B  B		signed, 15–19	The state of the s
ASICs. See Application-specific integrated circuits  Assembly language, MIPS. See MIPS assembly language  Associativity, 58–59  Average memory access time (AMAT), 467–468  Asynchronous circuits, 116–117  Asynchronous inputs, 144  Asynchronous resettable registers HDL for, 192  Axioms. See Boolean axioms  Betto end of the content of th	· · · · · · · · · · · · · · · · · · ·		
grated circuits Assembly language, MIPS. See MIPS assembly language, MIPS. See MIPS assembly language assembly language Associativity, 58–59 Average memory access time (AMAT), 467–468 Asynchronous circuits, 116–117 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Binary to decimal conversion, 12 Bit, 9–11  Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  C programming language, 290 overflows, 339 strings, 318 Caches, 468–484. See also Memory accessing, 472–477, 479 abse 2 number representations. See Binary numbers Base 8 number representations. See Octal numbers  Associativity, 58–59 Binary to decimal conversion, 12 Binary to hexadecimal conversion, 12 Bit, 9–11 Atheritable dirty, 482–483 Binary to hexadecimal conversion, 12 Bit, 9–11 Aintry, 482–483 Bits, 9–11 Aintry, 482–483 Bits, 9–11 Aintry, 482–483 Bits significant, 13–14 most significant, 13–14 mos	The state of the s		
Assembly language, MIPS. See MIPS assembly language unsigned, 9–15 unsigned, 9–15 Binary to decimal conversion, 467–468 Binary to hexadecimal conversion, 12 Big-Endian, 296–297 Big-Endian, 296–297 Little-Endian, 296–29 Little-End		=	
assembly language unsigned, 9–15 Byte-addressable memory, 295–297 Associativity, $58-59$ Binary to decimal conversion, $10-11$ Byte order, $296-297$ Big-Endian, $296-297$ Little-Endian, $296-297$ Little-Endian, $296-297$ Little-Endian, $296-297$ Asynchronous circuits, $116-117$ Bit, $9-11$ dirty, $482-483$ least significant, $13-14$ most significant, $13-14$ most significant, $13-14$ sign, $16$ use, $478-479$ valid, $472$ C programming language, $290$ overflows, $339$ strings, $318$ Bit swizzling, $182$ Bit wise operators, $171-174$ Boole, George, $8$ Boolean algebra, $56-62$ axioms, $57$ Base address, $295-296$ axioms, $57$ accessing, $472-473$ , $476-477$ , $479$ Base 2 number representations. See Binary numbers Boolean equations, $57$ Base 8 number representations. $800$ Boolean equations, $57-60$ blocks, $469-470$ , $476$ capacity, $468-470$ data placement, $469-470$		<u> </u>	
Associativity, 58–59 Average memory access time (AMAT), 467–468 Binary to hexadecimal conversion, 467–468 Binary to hexadecimal conversion, 12 Bity, 9–11 Asynchronous circuits, 116–117 Bit, 9–11 dirty, 482–483 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Byte order, 296–297 Big-Endian, 296–297 Little-Endian, 296–297  Little-Endian, 296–297  Composition of the state of the sta		<u>*</u>	
Average memory access time (AMAT), 467-468  Asynchronous circuits, 116-117  Asynchronous circuits, 144  Asynchronous resettable registers  HDL for, 192  Axioms. See Boolean axioms  Big-Endian, 296-297  Little-Endian, 296-29  C programming language, 290  overflows, 339  strings, 318  Caches, 468-484. See also Memory accessing, 472-473, 476-477, 479  advanced design, 479-483  associativity		9 .	
Asynchronous circuits, 116–117 Asynchronous inputs, 144 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Bit, 9–11  dirty, 482–483  least significant, 13–14  most significant, 13–14  sign, 16  use, 478–479  valid, 472  Bit cells, 258  Bit swizzling, 182  Bitwise operators, 171–174  Boole, George, 8  Boolean algebra, 56–62  Base address, 295–296  Base 2 number representations. See Binary numbers  Boolean axioms, 57  Base 8 number representations. See Octal numbers  Bit odd, 472  Bit cells, 258  Bit swizzling, 182  Bitwise operators, 171–174  Boole, George, 8  Boolean algebra, 56–62  axioms, 57  equation simplification, 61–62 theorems, 57–60  block size, 476–477 blocks, 469–470, 476 capacity, 468–470, 476 capacity, 468–470 data placement, 469–470		· · · · · · · · · · · · · · · · · · ·	•
Asynchronous circuits, 116–117 Asynchronous inputs, 144 Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  Bit, 9–11  dirty, 482–483  least significant, 13–14  most significant, 13–14  sign, 16  use, 478–479  valid, 472  Bit cells, 258  Bit swizzling, 182  Bitwise operators, 171–174  Boole, George, 8  Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers Boolean axioms, 57 Base 8 number representations. See Octal numbers  Boolean equations, 54–56  Boolean equations, 61–62  data placement, 469–470		Binary to hexadecimal conversion, 12	
Asynchronous inputs, 144  Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  B B B B B B B B B B B B B B B B B B			
Asynchronous resettable registers HDL for, 192 Axioms. See Boolean axioms  B B B B B B B B B B B B B B B B B B	· ·		
HDL for, 192  Axioms. See Boolean axioms  sign, 16 use, 478–479 valid, 472  Bit cells, 258 Bit swizzling, 182 Bitwise operators, 171–174 Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers Boolean axioms, 57 Base 8 number representations. See Octal numbers  most significant, 13–14 sign, 16 use, 478–479 valid, 472 C programming language, 290 overflows, 339 strings, 318 Caches, 468–484. See also Memory accessing, 472–473, 476–477, 479 advanced design, 479–483 associativity, 469, 474–475, block size, 476–477 blocks, 469–470, 476 capacity, 468–470 data placement, 469–470		**	
Axioms. See Boolean axioms       sign, 16			C
Bit cells, 258 Bit swizzling, 182 Bitwise operators, 171–174 Babbage, Charles, 7–8, 26 Boolean algebra, 56–62 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers Boolean and summer sums boolean equations, 54–56 Base 8 number representations. See Octal numbers  Bit cells, 258 Boolean algebra, 56–62 Boolean algebra, 56–62 Boolean axioms, 57 Boolean equations, 57–60 Boolean equations, 54–56 Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations. Boolean equations, 54–56 Capacity, 468–470 Bate 8 number representations.	,		
Bit cells, 258 Bit swizzling, 182 Bitwise operators, 171–174 Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers Boolean and self and a strong s		9 -	
Bit cells, 258 Bit swizzling, 182 Bit wise operators, 171–174 Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers Boolean axioms, 57 Base 8 number representations. See Octal numbers Bit cells, 258 Bit cells, 258 Bit swizzling, 182 Bit swizzling, 182 Strings, 318 Caches, 468–484. See also Memory accessing, 472–473, 476–477, 479 accessing, 472–473, 476–477, 479 associativity, 469, 474–475, block size, 476–477 blocks, 469–470, 476 capacity, 468–470 broduct-of-sums (POS) canonical data placement, 469–470			C programming language, 290
Bit swizzling, 182  Bit swizzling, 182  Bitwise operators, 171–174  Boole, George, 8  Boolean algebra, 56–62  Base address, 295–296  Base register, 302, 343, 347  Base 2 number representations.  See Binary numbers  Boolean axioms, 57  Boolean equations, 54–56  See Octal numbers  Boolean equations, 54–56  product-of-sums (POS) canonical  Both sxizings, 318  Caches, 468–484. See also Memory accessing, 472–473, 476–477, 479 associativity, 469, 474–475, block size, 476–477 blocks, 469–470, 476 capacity, 468–470 data placement, 469–470	_		1 0 0 0 0
Bitwise operators, 171–174 Babbage, Charles, 7–8, 26 Boolean algebra, 56–62 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations. See Binary numbers Boolean axioms, 57 Boolean equations, 54–56 Boolean equations, 54–56 See Octal numbers Boolean equations, 61–62 Boolean equations, 54–56	В		
Boole, George, 8 accessing, 472–473, 476–477, 479 Babbage, Charles, 7–8, 26 Boolean algebra, 56–62 advanced design, 479–483 Base address, 295–296 axioms, 57 associativity, 469, 474–475, Base register, 302, 343, 347 equation simplification, 61–62 478–479 Base 2 number representations. theorems, 57–60 block size, 476–477 See Binary numbers Boolean axioms, 57 blocks, 469–470, 476 Base 8 number representations. Boolean equations, 54–56 capacity, 468–470 See Octal numbers product-of-sums (POS) canonical data placement, 469–470		_	6 7
Babbage, Charles, 7–8, 26 Base address, 295–296 Base register, 302, 343, 347 Base 2 number representations.  See Binary numbers Boolean axioms, 57 Boolean equations, 54–56 See Octal numbers  Product-of-sums (POS) canonical  Boolean advanced design, 479–483 associativity, 469, 474–475, 478–479 block size, 476–477 blocks, 469–470, 476 capacity, 468–470 data placement, 469–470			
Base address, 295–296 axioms, 57 associativity, 469, 474–475, Base register, 302, 343, 347 equation simplification, 61–62 478–479 Base 2 number representations. theorems, 57–60 block size, 476–477 See Binary numbers Boolean axioms, 57 blocks, 469–470, 476 Base 8 number representations. Boolean equations, 54–56 capacity, 468–470 See Octal numbers product-of-sums (POS) canonical data placement, 469–470	Babbage, Charles, 7–8, 26		
Base register, 302, 343, 347 equation simplification, 61–62 478–479 Base 2 number representations. theorems, 57–60 block size, 476–477 See Binary numbers Boolean axioms, 57 blocks, 469–470, 476 Base 8 number representations. Boolean equations, 54–56 capacity, 468–470 See Octal numbers product-of-sums (POS) canonical data placement, 469–470	9 7 7	<u> </u>	ē .
Base 2 number representations. theorems, 57–60 block size, 476–477  See Binary numbers Boolean axioms, 57 blocks, 469–470, 476  Base 8 number representations. Boolean equations, 54–56 capacity, 468–470  See Octal numbers product-of-sums (POS) canonical data placement, 469–470			
See Binary numbersBoolean axioms, 57blocks, 469–470, 476Base 8 number representations.Boolean equations, 54–56capacity, 468–470See Octal numbersproduct-of-sums (POS) canonicaldata placement, 469–470	0 , , ,	• •	
Base 8 number representations. Boolean equations, 54–56 capacity, 468–470 See Octal numbers product-of-sums (POS) canonical data placement, 469–470			
See Octal numbers product-of-sums (POS) canonical data placement, 469–470	•		
	-	1	1 ,,
	211 2 1111 111110010		data replacement, 478–479

definition, 468	pipelining, 152	transistors, 26–34
direct mapped, 470–474	priority, 65, 202, 203	Complex instruction set computers
dirty bit, 482–483	synchronous sequential, 114–116	(CISC), 292, 341
entry fields, 472–473	synthesized, 186–190, 193–195,	Compulsory miss, 481
evolution of MIPS, 483	199, 200	Computer-aided design (CAD), 167
fully associative, 475–476	timing, 84–91	Computer Organization and Design
hit, 466	timing analysis, 138	(Patterson and Hennessy),
hit rate, 467	types, 51–54	290, 363
IA-32 systems, 499–500	without glitch, 91	Complexity management, 4–6
level 2 (L2), 480	CISC. See Complex instruction set	abstraction, 4–5
mapping, 470–478	computers	discipline, 5–6
miss, 466	CLBs. See Configurable logic blocks	hierarchy, 6
capacity, 481	Clock cycle. See Clock period	modularity, 6
compulsory, 481	Clock period, 135–139	regularity, 6
conflict, 481	Clock rate. See Clock period	Conditional assignment, 175-176
miss rate, 467	Clock cycles per instruction (CPI),	Conditional branches, 308
miss rate versus cache parameters,	367–368	Condition codes, 344
481–482	Clustered computers, 447	Conflict misses, 481
miss penalty, 476	Clock skew, 140–143	Conditional statements, 310–311
multiway set associative, 474-475	CMOS. See Complementary Metal-	Constants, 298. See also Immediates
nonblocking, 500	Oxide-Semiconductor Logic	Contamination delay, 84–88
organizations, 478	Code, 303	Contention (X), 69–70
performance, 467	Code size, 334	Context switch, 446
set associative, 470, 474–475	Combinational composition, 52–53	Control signals, 79, 242–243
tag, 471–472	Combinational logic design, 51-100	Control unit, 364, 366, 374–406
use bit, 478–479	Boolean algebra, 56–62	multicycle MIPS processor FSM,
valid bit, 472–473	Boolean equations, 54–56	381–395
write policy, 482–483	building blocks, 79–84	pipelined MIPS processor, 405–406
CAD. See Computer-aided design	delays, 85–87	single-cycle MIPS processor,
Canonical form, 53	don't cares, 65	374–377
Capacitors, 28	HDLs and. See Hardware descrip-	Configurable logic blocks (CLBs),
Capacity miss, 481	tion languages	268–272
Carry-lookahead adder, 235–237	Karnaugh maps, 71–79	Control hazards. See Branch/control
Carry propagate adder (CPA), 274	logic, 62–65	hazards, Pipelining
Cathodes, 27–28	multilevel, 65–69	Coprocessor 0, 338
Cause register, 337–338	overview, 51–54	Counters, 254
Chips, 28, 449	precedence, 54	Covalent bond, 27
74xx series logic. See 74xx series	timing, 84–91	CPA. See Carry propagate adder
logic	two-level, 65–66	CPI. See Clock cycles per instruction
Circuits, 82–83, 87–88	X's (contention). See Contention	Critical path, 85–89
74xx series logic. See 74xx series	X's (don't cares). See Don't cares	Cyclic paths, 114
logic	Z's (floating). See Floating	Cycle time. See Clock Period
application-specific integrated	Comparators, 240–241	
(ASIC), 523	equality, 241	
arithmetic. See Arithmetic	magnitude, 241, 242	D
asynchronous, 116–117	Compiler, 331–333	
bistable device, 147	Complementary Metal-Oxide-	
combinational, 53	Semiconductor Logic (CMOS), 25	D 1 1 0 11 1
definition, 51	bubble pushing, 69	Data hazards. See Hazards
delays, 73–75, 84–87	logic gates, 31–33	Data memory, 365
calculating, 86–87	NAND gate, 32	Data sheets, 523–528
dynamic, 273	NOR gate, 32–33	Datapath, 364. See also MIPS micro-
multiple-output, 64	NOT gate, 31	processors

Datapath (Continued)	breadboards, 532	Erasable programmable read only
elements, 364	packages, 531-532	memory (EPROM), 263
multicycle MIPS processor, 382–388	printed circuit boards, 533–534	Exceptions, 337–339
pipelined MIPS processor, 404	programmable logic, 516–523	Exception handler, 337-338
single-cycle MIPS processor,	transmission lines. See Transmission	Exception program counter (EPC),
368–374	lines	337–338
Data segments. See Memory map	Diodes, 27–28	Exclusive or. See XOR
Data types. See Hardware description	DIP. See Dual-inline package	Executable file, 334
languages	Direct current (DC), 23, 24	Execution time, 367
DC. See Direct current	transfer characteristics, 23–24, 25	Exponent, 250–253
Decimal numbers, 9	Direct mapped cache, 470–474	1
conversion to binary and hexadeci-	Dirty bit, 482–483	
mal. See Number conversion	Discipline, 5–6	_
scientific notation, 249–250	Disk. See Hard disk	F
Decimal to Binary conversion, 11	divide (div), 308	
Decimal to hexadecimal conversion, 13	divide unsigned (divu), 339	
Decoders	Divider, 247–248	Failures, 144–146
implementation, 83	Division, 247–248	FDIV bug, 253
logic, 83	floating-point, 253	FET. See Field effect transistors
parameterized, 212	instructions, 308	Field programmable gate array (FPGA),
Deep pipelines, 435–436	Divisor, 247	268–272, 521–523
Delay, 182	Don't care (X), 65	Field effect transistors, 26
DeMorgan, Augustus, 56	Dopant atoms, 27	FIFO. See First-in-first-out queue. See
DeMorgan's theorem, 59, 60	Double. See Double-precision floating-	also Queue
Dennard, Robert, 260	point numbers	Finite state machines (FSMs),
Destination register, 301, 305–306,	Double-precision floating point num-	117–133
370–371, 377–378	bers, 251–252	design example, 117–123
Device under test (DUT), 214–218.	DRAM. See Dynamic random access	divide-by-3, 207–208
See also Unit under test	memory	factoring, 129–132
Device driver, 496, 498	Driver. See Device driver	HDLs and, 206–213
Dice, 28	Dual-inline package (DIP), 28, 531	Mealy machines. See Mealy machines
Digital abstraction, 4–5, 8–9, 22–26	DUT. See Device under test	Moore machines. See Moore
DC transfer characteristics, 23–24	Dynamic discipline, 134	machines
logic levels, 22–23	Dynamic data segment, 331	Moore versus Mealy machines,
noise margins, 23	Dynamic random access memory	126–129
supply voltage, 22	(DRAM), 257, 260, 463	state encodings, 123–126
Digital design	(DRIMI), 257, 200, 103	state transition diagram, 118–119
abstraction, 7–9		First-in-first-out (FIFO) queue, 508
discipline, 5–6		Fixed-point numbers, 249–250
hierarchy, 6	E	Flash memory, 263–264
modularity, 6		Flip-flops, 103–112, 257. See also
regularity, 6		Registers
Digital system implementation, 515–548	Edison, Thomas, 169	comparison with latches, 106, 112
74xx series logic. See 74xx series	Edge-triggered digital systems,	D, 108
logic	108, 112	enabled, 109–110
application-specific integrated	Equations	register, 108–109
circuits (ASICs), 523	simplification, 61–62	resettable, 110, 427
data sheets, 523–528	Electrically erasable programmable read	asynchronous, 192
economics, 546–548	only memory (EEPROM), 263	synchronous, 192
logic families, 529–531	Enabled registers, 193	transistor count, 108
overview, 515	HDL for, 193	transistor count, 108 transistor-level, 110–111
packaging and assembly,	EPC. See Exception Program Counter	Floating (Z), 69–71
531–534	register	Floating-point numbers, 250–253
JJ1 JJ1	10513101	From Point numbers, 200–200

addition, 252-255. See also	H	Hazards, 75, 406-418. See also
Addition		Glitches
converting binary or decimal to. See		control hazards, 413-416
Number conversions	Half word, 339	data hazards 408–413
division, 253. See also Division	Half adder, 233–234	solving, 408–416
double-precision, 251–252	Hard disk, 484	forwarding, 408–410
FDIV bug. See FDIV bug	Hard drive. See Hard disk	stalls, 410-413
floating-point unit (FPU), 253	Hardware reduction, 66–67	WAR. See Write after read
instructions, 340–341	Hardware description languages	WAW. See Write after write
rounding, 252	(HDLs), 167–230	Hazard unit, 408, 411, 419
single-precision, 251–252	assignment statements, 177	Heap, 331
special cases	behavioral modeling, 171–184	HDLs. See Hardware description
infinity, 251	combinational logic, 171–185,	languages
not a number (NaN), 251	195–206	Hennessy, John, 290, 364
Forwarding, 408–409	bit swizzling, 182	Hexadecimal numbers, 11–13
Fractional numbers, 274	bitwise operators, 171–174	to binary conversion table, 12
FPGA. See Field programmable gate	blocking and nonblocking	Hierarchy, 6, 189
array	assignments, 201–206	HIGH, 23. See also 1, ON
Frequency, 135. See also Clock period	case statements, 198–199	High-level programming languages,
FSM. See Finite state machines	conditional assignment, 175–176	290–294
Full adder, 52, 178. See also Adder,	delays, 182–183	translating into assembly, 290-291
Addition	if statements, 199–201	compiling, linking, and launching,
HDL using always/process, 197	internal variables, 176–178	330–331
using nonblocking assignments,	numbers, 179	Hit, 466
204	precedence, 178–179	High impedance. See Floating, Z
Fully associative cache, 475–476	reduction operators, 174	High Z. See Floating, High
Funct field, 299–300	synthesis tools. See Synthesis Tools	impedance, Z
Functional specification, 51	Verilog, 201	Hold time, 133–154
Functions. See Procedure calls	VHDL libraries and types,	
Fuse, 263	183–185	
	Z's and X's, 179–182	1
	finite state machines, 206–213	•
G	generate statement, 213	
u	generic building blocks, 426	1
	invalid logic level, 181	I-type instruction, 301–302
6 . 10.22	language origins, 168–169	IA-32 microprocessor, 290, 341–349,
Gates, 19–22	modules, 167–168	447–453
AND, 20–22, 32–33	origins of, 168–169	branch conditions, 346
NAND, 21, 32	overview, 167	cache systems, 499–500
NOR, 21, 32–33	parameterized modules, 211-213	encoding, 346–348
OR, 21	representation, 421–431	evolution, 448, 500
transistor-level implementation, 262	sequential logic, 190-195, 205	instructions, 344, 345
XOR, 21	enabled registers, 193	memory and input/output (I/O) systems, 499–502
XNOR, 21 Gedanken-Experiments on Sequential	latches, 195	operands, 342–344
Machines (Moore), 111	multiple registers, 194–195	programmed I/O, 502
Generate signal, 235, 237	registers, 190-191. See also	registers, 342
Glitches, 75, 88–91	Registers	status flags, 344
Global pointer (\$gp), 294, 331. See	resettable registers, 191–193	virtual memory, 501
also Static data segment	simulation and synthesis, 169-171	IEEE 754 floating-point standard, 251
Gray, Frank, 65	single-cycle processor, 422	Idempotency, 58
Gray codes, 65, 72	structural modeling, 185-189	Idioms, 171
Gulliver's Travels (Swift), 297	testbenches, 214-218, 428-431	IEEE, 169
Gumver's fravers (Swift), 277		11111, 107

If statements, 199–201, 310	Integrated circuits (ICs), 26, 137,	Last-in-first-out (LIFO) queue, 321. See
If/else statements, 311	515, 532	also Stack, Queue
ILP. See Instruction-level parallelism	costs, 137, 169	Latches, 103–112
Immediates, 298	manufacturing process, 515	comparison with flip-flops, 106, 112
Immediate addressing, 327	Intel. See IA-32 microprocessors	D, 107
Information, amount of, 8	Interrupts. See Exceptions	SR, 105–107
IorD, 385	An Investigation of the Laws of	transistor-level, 110–111
I/O (input/output), 337, 494–502	Thought (Boole), 8	Latency, 149
communicating with, 494–495	Involution, 58	Lattice, 27
device driver, 496, 498	IOBs. See Input/output blocks	Leaf procedures, 324–325
devices, 494–496. See also	I-type instructions, 301–302	Least recently used (LRU) replacement,
Peripheral devices		478–479
memory interface, 494, 502		Least significant bit (lsb), 13
memory-mapped I/O, 494-499	J	Least significant byte (LSB), 296
Inputs, asynchronous, 144–145		LIFO. See Last-in-first-out queue
Instruction encoding. See Machine		Literal, 54, 61, 167
Language		Little-Endian, 296–297
Instruction register (IR), 383, 390	Java, 316. See also Language	Load, 255
Instruction set architecture (ISA),	JTA. See Jump target address	byte (1b), 317
289–361. See also MIPS instruc-	J-type instructions, 302	byte unsigned (1bu), 317
tion set architecture	Jump, 309-310. See also Branch,	half (1h), 339
Input/output blocks (IOBs), 268	unconditional, Programming	immediate (11), 336
Input terminals, 51	Jump target address (JTA), 329	upper immediate (141), 308
Institute of Electrical and Electronics		word (1w), 295–296
Engineers, 250	V	Loading, 335
Instruction decode, 401–402	K	Locality, 464
Instruction encoding. See Instruction		Local variables, 326–327
format		Logic, 62-65. See also Multilevel com-
Instruction format	K-maps. See Karnaugh maps	binational logic; Sequential logic
F-type, 340	Karnaugh, Maurice, 64, 71	design
I-type, 301–302	Karnaugh maps (K-maps), 71-79	bubble pushing. See Bubble pushing
J-type, 302	logic minimization using, 73–76	combinational. See Combinational
R-type, 299–300	prime implicants, 61, 74	logic
Instruction-level parallelism (ILP), 443,	seven-segment display decoder,	families, 529–531
446	75–77	gates. See Logic gates
Instruction memory, 365	with "don't cares," 78	hardware reduction. See Hardware
Instruction set. See Instruction set	without glitches, 91	reduction, Equation simplifi-
architecture	Kilby, Jack, 26	cation
Instructions. See also Language	Kilobyte, 14	multilevel. See Multilevel combina-
arithmetic/logical, 304–308	· ·	tional logic
floating-point, 340–341	K-maps. See Karnaugh maps	programmable, 516–523
IA-32, 344–346		sequential. See Sequential logic
I-type, 301–302		synthesis, 170–171
J-type, 302	L	two-level, 65–66
loads. See Loads		using memory arrays, 264. See also
multiplication and division, 308		Logic arrays
	Labels, 308-309	
pseudoinstructions, 336–337		Logic arrays, 266–274
R-type, 299–300	Language. See also Instructions	field programmable gate array,
set less than, 339	assembly, 290–299	268–272
shift, 306–307	high-level, 290–294	programmable logic array, 266–268
signed and unsigned, 338–339	machine, 299–304	transistor-level implementations,
Intel, 30, 111, 290, 348, 367	mnemonic, 291	273–274
Inverter. See NOT gate	translating assembly to machine, 300	Logic families, 25, 529–531

compatibility, 26	Main decoder, 374–379	Memory arrays, 257–266
specifications, 529, 531	Main memory, 466–469	area, 261
Logic gates, 19–22, 173	Mapping, 470	bit cells, 258
buffer, 20	Mantissa, 250, 252-253. See also	delay, 261
delays, 183	Floating-point numbers	DRAM. See Dynamic random
multiple-input gates, 21–22	Masuoka, Fujio, 263	access memory
two-input gates, 21	MCM. See Multichip module	HDL code for, 264–266
types	Mealy, George H., 111	logic implementation using, 264.
AND. See AND gate	Mealy machines, 126–129, 130, 210	See also Logic arrays
AOI (and-or-invert).	combined state transition and	organization, 258
See And-or-invert gate	output table, 127	overview, 257–260
NAND. See NAND gate	state transition diagram, 118–119	ports, 259
NOR. See NOR gate	timing diagram, 131	register files built using, 261–262
NOT. See NOT gate	Mean time between failures (MTBF),	types, 259–260
OAI (or-and-invert).	146	DRAM. See Dynamic random
See Or-and-invert gate	Memory, 51, 295–298	access memory
OR. See OR gate	access, 298	ROM. See Read only memory
XOR. See XOR gate	average memory access time	SRAM. See Static random access
XNOR. See XNOR gate	(AMAT), 467	memory
Logic levels, 22–23	cache. See Caches	Memory-mapped I/O (input/output),
Logical operations, 304–308	DRAM. See Dynamic random	494–498
Lookup tables (LUTs), 268	access memory	address decoder, 495–496
Loops, 311–314	hierarchy, 466	communicating with I/O devices,
for, 313	interface, 464	495–496
while, 312–313	main, 466–469	hardware, 495
LOW, 23. See also 0, OFF	map, 330–331	speech synthesizer device driver,
Low Voltage CMOS Logic	dynamic data segment, 331	498
(LVCMOS), 25	global data segment, 330–331	speech synthesizer hardware,
Low Voltage TTL Logic (LVTTL), 25	reserved segment, 331	496–497
LRU. See Least recently used replacement	text segment, 330	SP0256, 496
LSB. See Least significant byte	nonvolatile, 259–260	Memory protection, 491
LUTs. See Lookup tables	performance, 465	Memory systems, 463–512
LVCMOS. See Low Voltage CMOS	physical, 466, 485–486	caches. See Caches
Logic	protection, 491. See also Virtual	IA-32, 499–502
LVTTL. See Low Voltage TTL Logic	memory	MIPS, 470–478
	RAM, 259	overview, 463–467
	ROM, 259	performance analysis, 467–468
M	separate data and instruction,	virtual memory. See Virtual
	430–431	memory
	shared, 71	Mercedes Benz, 268
Marking language 200, 204	stack. See Stack	Metal-oxide-semiconductor field effect
Machine language, 299–304	types	transistors (MOSFETs), 26–31.
function fields, 299	flip-flops, 105–112	See also CMOS, nMOS, pMOS,
interpreting code, 302–303	latches, 105–112	transistors
I-type instructions, 301–302	DRAM, 257	Metastability, 143–144  MTBF. See Mean time between
J-type instructions, 302 opcodes, 299–303	registers, 108–109 register file, 261–262	failures
R-type instructions, 299–300	SRAM, 257	metastable state, 143
stored programs, 303–304	virtual, 466. <i>See also</i> Virtual	probability of failure, 145
translating from assembly language,	memory	resolution time, 144
300–302	volatile, 259–261	synchronizers, 144–146
translating into assembly	word-addressable, 29. See Word-	A Method of Synthesizing Sequential
language, 303	addressable memory	Circuits (Mealy), 111
ianguage, 505	addressable memory	Circuits (Meary), 111

Microarchitecture, 290, 363-461	addressing modes, 327–329	testbench, 429
advanced. See Advanced	assembly language, 290-299	top-level module, 430
microarchitecture	compiling, assembling, and loading,	Misses, 466, 481
architectural state. See Architectural	330–335	AMAT. See Average memory access
State. See also Architecture	exceptions, 337–338	time
design process, 364–366	floating-point instructions, 340–341	cache, 466
exception handling, 431–434	IA-32 instructions, 344–346	capacity, 481
HDL representation, 421–431.	machine language, 299–304	compulsory, 481
IA-32. See IA-32 microprocessor	MIPS instructions, 290–292	conflict, 481
instruction set. See Instruction set	overview, 289–290	page fault, 485
MIPS. See MIPS microprocessor	programming, 304–327	Miss penalty, 476
overview, 363–366	pseudoinstructions, 336–337	Miss rate, 467
performance analysis, 366–368	signed and unsigned instructions,	Mnemonic, 291
types,	338–339	Modeling, structural. See Structural
advanced. See Advanced	SPARC, 364	modeling
microarchitecture	translating and starting a program.	Modeling, behavioral. See Behavioral
multicycle. See Multicycle MIPS	See Translating and starting	modeling
processor	a program	Modularity, 6, 168
pipelined. See Pipelined MIPS	MIPS instructions, 551–554	Modules, in HDL 167–168. See also
processor	formats	Hardware description
single-cycle. See Single-cycle	F-type, 340	languages
	I-type, 340	0 0
MIPS processor Microprocessors, 3, 13	*1	behavioral, 168, 171 parameterized, 211–213
advanced. See Advanced	J-type, 302	•
	R-type, 299–300	structural, 168
microarchitecture	tables of, 552–554	Moore, Edward F., 111
chips. See Chips	opcodes, 552	Moore, Gordon, 30
clock frequencies, 124	R-type funct fields, 553–554	Moore machine, 126–129, 130,
IA-32. See IA-32 microprocessor	types,	208, 209
instructions. See MIPS instructions,	arithmetic, 304–308	output table, 128
IA-32 instructions	branching. See Branching	state transition diagram, 127
MIPS. See MIPS microprocessor	division, 308	state transition table, 128
Microsoft Windows, 501	floating-point, 340–341	timing diagram, 131
Minterms, 54	logical, 304–308	Moore's law, 30
Maxterms, 54	multiplication, 308	MOSFETs. See Metal-oxide-semicon-
MIPS (Millions of instructions per	pseudoinstructions, 336–337	ductor field effect transistors
second). See Millions of	MIPS microprocessor, 364	Most significant bit (msb), 13
instructions per second	ALU, 242–244	Most significant byte (MSB), 296
MIPS architecture. See MIPS	multicycle. See Multicycle MIPS	Move from hi (mfhi), 308
instruction set architecture (ISA)	processor	Move from lo (mflo), 308
MIPS assembly language. See also	pipelined. See Pipelined MIPS	Move from coprocessor 0 (mfc0), 338
MIPS instruction set	processor	msb. See Most significant bit
architecture	single-cycle. See Single-cycle MIPS	MSB. See Most significant byte
addressing modes, 327-329	processor	MTBF. See Mean time before failure
assembler directives, 333	MIPS processor. See MIPS micro-	Multichip module (MCM), 499
instructions, 290–292	processor	Multicycle MIPS processor, 366,
logical instructions, 304–308	MIPS registers, 293–294, 308	381-400
mnemonic, 291	nonpreserved, 322–324	control, 388-394
operands, 292–298	preserved, 322–324	control FSM, 394–395
procedure calls, 319–327	table of, 294	datapath, 382-388
table of instructions, 336	MIPS single-cycle HDL implemen-	performance analysis, 397–400
translating machine language to, 303	tation, 421–431	Multilevel combinational logic, 65–69.
translating to machine language, 300	building blocks, 426-428	See also Logic
MIPS instruction set architecture	controller, 423	Multilevel page table, 493
(ISA)	datapath, 425	Multiplexers, 79–82, 175, 176, 428

instance, 188	addition. See Addition	Output terminals, 51
logic, 80–82	binary numbers. See Binary numbers	Overflow, 15
parameterized, 211. See also	comparison of, 18–19	detecting, 15
Hardware description	conversion of. See Number	with addition, 15
languages	conversions	
symbol and truth table, 79	decimal numbers. See Decimal	n
timing, 87–88	numbers	P
with type conversion, 185	estimating powers of two, 14	
wide, 80	fixed-point, 249-250. See Fixed-	
Multiplicand, 246	point numbers	Page, 485
Multiplication, 246–247. See also	floating-point, 250–253. See	size, 485
Arithmetic, Multiplier	Floating-point numbers	Page fault, 485
architecture, 339	in hardware description languages,	Page offset, 486–488
instructions, 308	179	Page table, 486
Multiplier, 246–247	hexadecimal numbers. See	Parity, 22
multiply (mult), 308, 339	Hexadecimal numbers	Parallelism, 149–153
	negative and positive, 15–19	
multiply unsigned (multu), 339		pipelining. See Pipelining, Pipelined
Multiprocessors, 447	rounding, 252. See also Floating-	MIPS processor
chip, 448	point numbers	SIMD. See Single instruction
Multithreading, 446	sign bit, 16	multiple data unit
Mux. See Multiplexers	signed, 15–19. See also Signed	spatial and temporal, 151
	binary numbers	vector processor. See Vector processor
	sign/magnitude numbers. See	Patterson, David, 290, 364
N	Sign/magnitude numbers	PCBs. See Printed circuit boards
N	two's complement numbers. See	PC-relative addressing, 327–328.
	Two's complement	See also Addressing modes
	numbers	PCSrc, 281, 387–390
NaN. See Not a number	unsigned,	PCWrite, 385
Negation, 340. See also Taking the		Pentium processors, 449-452. See also
two's complement		Intel, IA-32
Not a number (NaN), 251	•	Pentium 4, 452
NAND gate, 21, 32	0	Pentium II, 450, 499
nor, 179		Pentium III, 450, 451, 499
NOR gate, 21, 32–33		Pentium M, 453
NOT gate, 24, 172. See also Inverter	OAI gate. See Or-and-invert gate	Pentium Pro, 450, 499, 501
in HDL using always/process, 196	Object files, 331–334	Perfect induction, 60
Nested procedure calls, 324–326	Octal numbers, 180	Performance, 366–368
Netlist, 170	OFF, 23. See also 0, LOW	Peripheral devices. See I/O devices
Next state, 115	Offset, 295–296	Perl programming language, 20
Nibbles, 13–14	ON, 23. See also 1, HIGH, Asserted	Physical memory, 466, 485–486
nMOS, 28–31	One-cold, 124	Physical pages, 486–494
nMOS transistors, 28–31	One-hot, 82	Physical page number, 486
	Opcode, 299	Pipelined MIPS processor, 151, 366,
No operation. See nop	± .	
Noise margins, 23, 24	Operands, 292–298	401–421. See also MIPS,
nop, 336	Operators	Architecture, Microarchitecture
Noyce, Robert, 26	bitwise, 171–174	control, 405–406
Number conversion, 9–19 See also	or immediate (ori), 308	datapath, 404
Number systems, Binary numbers	OR gate, 21	forwarding, 408–410
binary to decimal, 10–11	Or-and-invert (OAI) gate, 43	hazards. See Hazards
binary to hexadecimal, 12	precedence table of, 179	performance analysis, 418–421
decimal to hinary 11		
decimal to binary, 11	reduction, 174	processor performance
decimal to hexadecimal, 13	reduction, 174 Out-of-order execution, 443	comparison, 420
decimal to hexadecimal, 13 taking the two's complement, 15, 240	reduction, 174 Out-of-order execution, 443 Out-of-order processor, 441–443	comparison, 420 stalls, 410–413. <i>See also</i> Hazards
decimal to hexadecimal, 13	reduction, 174 Out-of-order execution, 443	comparison, 420

Pipelining hazards. See Hazards translating and starting a program, Reduction operators, 174, See also PLAs. See Programmable logic arrays 331-335 Hardware description languages, Plastic leaded chip carriers (PLCCs), Programming languages, 290-294 Verilog 531-532 Propagation delay, 84 RegDst, 373-374 PLCCs. See Plastic leaded chip carriers Protection, memory. See Memory Register-only addressing, 327. See also PLDs. See Programmable logic devices Addressing modes protection pMOS, 29-30 Proving Boolean theorems. See Perfect Register renaming, 443–445. See also pMOS transistors, 28-31 Advanced microarchitecture induction Pointer, 321 PROMs. See Programmable read only Register(s), 190-191, 261-262, global, 331 memories 292-294. See also Flip-flops, stack, 321 Pseudo-direct addressing, 328-329. Register file Pop, 345-346. See also Stack See also Addressing modes arguments (\$a0-\$a3) Ports, 259 Pseudo-nMOS logic, 33-34. See also assembler temporary (\$at) POS. See Product of sums form Transistors enabled. See Enabled registers Power consumption, 34–35 Pseudoinstructions, 336-337 file, 261 Prediction. See Branch prediction Push, 67-69. See also Stack global pointer (\$gp), 331 Prefix adder, 237-239 multiple, 194-195 Preserved registers, 322-324 program counter (PC), 365 Prime implicants, 61, 74 preserved and nonpreserved. 0 Printed circuit boards (PCBs), 322-324 533-534 renaming, 443-445 Procedure calls, 319-327 resettable. See Resettable registers Queue, 321 arguments and variables, 326-327 asynchronous, 192 FIFO. See First-in-first-out queue synchronous, 192 nested, 324-326 LIFO. See Last-in-first-out queue preserved versus nonpreserved return address (\$ r a), 319-320 Q output. See Sequential logic design Register set, 294. See also Register file, registers, 323-324 returns, 319-320 MIPS registers, IA-32 registers return values, 320 Regularity, 6, 188 R stack frame, 322 RegWrite, 371 stack usage, 321-322 Replacement policies, 492. See also Processors. See Microprocessors Caches, Virtual memory Product-of-sums (POS) canonical R-type instructions, 299–300 Resettable registers, 191-193 form, 56 RAM. See Random access memory asynchronous. See Asynchronous Program counter (PC), 365 Random access memory (RAM), 257, resettable registers Programmable logic arrays (PLAs), 63, 262-264. See also Memory synchronous. See Synchronous 266-268, 520-521 resettable registers arrays Programmable logic devices synthesized, 265 Return address (\$ra), 319-320 (PLDs), 268 Read only memory, 199, 257, 262-264. Ripple-carry adder, 234 Programmable read only memories RISC. See Reduced instruction set See also Memory arrays (PROMs), 516-520. See also EPROM. See Erasable programmacomputer Read only memories ble read only memory ROM, See Read Only Memory Programming, 304–327 EEPROM. See Electrically erasable Rotators, 244-246 arithmetic/logical instructions. See programmable read only Rounding, 252 Arithmetic, 304-308 memory flash memory. See Flash memory arrays. See Arrays branching. See Branching PROM. See Programmable read S conditional statements. See only memory Conditional statements transistor-level implementation, 273 constants, 307-308 Read/write head, 484 immediates, 298 Recursive procedure calls, 324–325. Scalar processor, 438 See also Procedure calls loops. See Loops Scan chains, 255. See also Shift registers procedure calls. See Procedure calls Reduced instruction set computer Schematic, 62-65 shift instructions, 306-307 (RISC), 292, 364 Scientific notation, 249-250

Seek time, 484	Silicon (Si), 27	Sum-of-products (SOP) canonical form,
Segments, memory, 330–331	Silicon dioxide (SO <sub>2</sub> ), 28	54–55
Semiconductor industry, sales, 3	Silicon Valley, 26	Sun Microsystems, 364
Semiconductors, 27. See also	Simplicity, 291–292	Superscalar processor, 438–440
Transistors	SIMD. See Single instruction multiple	Supply voltage, 22
CMOS. See Complementary metal	data units	Swap space, 492
oxide silicon	Single-cycle MIPS processor, 366,	Swift, Jonathan, 297
diodes. See Diodes	368-381. See also MIPS micro-	Switch/case statements, 311
transistors. See Transistors	processor, MIPS architecture,	Symbol table, 333
MOSFET. See Metal oxide silicon	MIPS microarchitecture	Synchronizers, 144–146
field effect transistors	control, 374–377	asynchronous inputs, 146
nMOS. See nMOS transistors	ALU decoder truth table. See	MTBF. See Mean time before
pMOS. See pMOS transistors	ALU decoder	failure
pseudo nMOS. See Pseudo nMOS	Main decoder truth table. See	probability of failure. See
Sensitivity list, 190, 191, 196	Main decoder	Probability of failure
Sequential building blocks.	datapath, 368-374	Synchronous resettable registers, 192
See Sequential logic	HDL representation, 422	HDL for, 192
Sequential logic, 103–165, 190–195,	operation, 376–377 performance	Synchronous sequential logic,
254–257	analysis, 380–381	113–117
enabled registers, 193	timing, 402	problematic circuits, 113–114
latches, 103–112, 195	Single instruction multiple data (SIMD)	Synthesis, 78–79, 186, 187, 188, 189,
multiple registers, 194–195	units, 438, 445	190, 193, 194, 195, 199, 200
overview, 103	Slash notation, 53	Synthesis Tools, 195
registers, 190–191	SPARC architecture, 364	,
shift registers, 255–257	SRAM. See Static random access	
synchronous, 113–117	memory	_
timing of, 133-149. See also Timing	SP0256, 496	T
set if less than (slt), 313	Spatial locality, 464	
set if less than immediate (slti), 339	Speech synthesis, 496–498	
set if less than immediate unsigned	device driver, 498	Taking the two's complement, 16
(sltiu), 339	SP0256, 496	Temporal locality, 464
set if less than unsigned (sltu), 339	Stack, 321–322. See also Memory map,	Testbenches, 171, 214–218, 428–431
Setup time, 133, 135–136	Procedure calls, Queue	self-checking, 215
Seven-segment display decoder, 75–77	dynamic data segment, 331	with test vector file, 216
with "don't cares," 78	frame, 322	Text segment, 330
Shared memory, 71	LIFO. See Last-in-first-out queue	Theorems. See Boolean Theorems
Shift amount (shamt), 245	pointer, 321	Thin small outline package (TSOP), 531
shift left logical (\$11), 306	Stalls, 410–413. See also Hazards	Threshold voltage, 29
shift left logical variable (sllv), 306	Static discipline, 24–26	Throughput, 149
shift right arithmetic (sra), 306	Static random access memory (SRAM),	Timing
shift right arithmetic variable (srav), 306	257, 260	analysis, 137–138
shift right logical (srl), 306	Status flags, 344	delay, 86–87
shift right logical variable (srlv), 306	Stored program concept, 303–304	glitches, 88–91
Shifters, 244–246	Stores	of sequential logic, 133–149
arithmetic, 244	store byte (sb), 318	clock skew, 140–143
logical, 244	store half (sh), 553	dynamic discipline, 134
Shift instructions, 306–307	store word (sw), 296	hold time. See Hold time
Shift registers, 255–257	Strings, 318	hold time constraint, 136–137.
Short path, 86	Structural modeling, 185–189	See Hold time constraint,
Sign/magnitude numbers, 15–16	subtract (sub), 291	Hold time violation
Sign bit, 16	subtract unsigned (subu), 339	hold time violation. See Hold
Sign extension, 18	Subtraction, 17–18, 240, 291	time violation, Hold time
Significand. See Mantissa	Subtractor, 240	constraint, 139

Timing (Continued)	U	eight-input AND, 174
metastability, 143–144		entity declaration, 168
setup time. See Setup time		full adder, 178
setup time constraint,		using always/process, 197
135–136	Unconditional branches, 308. See also Jumps	using nonblocking assignments,
setup time violations	Unicode, 316. See also ASCII	204
resolution time, 146–149. See	Unit under test (UUT), 201	IEEE_STD_LOGIC_1164, 168, 183
also Metastability	· · · · · · · · · · · · · · · · · · ·	IEEE_STD_LOGIC_SIGNED, 183
synchronizers, 144–146	Unity gain points, 24	IEEE_STD_LOGIC_UNSIGNED,
system timing, 135–140	Unsigned numbers, 18	183
specification, 51	Use bit, 478–479	inverters, 172
TLB. See Translation lookaside	UUT. See Unit under test	using always/process, 196
buffer		left shift, 427
Token, 149		library use clause, 168
Transistors, 23, 28–31, 34	V	logic gates, 173
CMOS. See Complement metal		with delays, 183
oxide silicon		main decoder, 424
nMOS. See nMOS	Valid bit, 472. See also Caches, Virtual	MIPS testbench, 429
pMOS. See pMOS	memory	MIPS top-level module, 430
Transistor-Transistor Logic (TTL), 25	Vanity Fair (Carroll), 65	multiplexers, 175, 176, 428
Translation lookaside buffer (TLB),		
490	V <sub>CC</sub> , 23	multiplier, 247 nonblocking assignment, 191,
***	V <sub>DD</sub> , 23	9 9
Translating and starting a program,	Vector processors, 438. See also	202 NOT 168
331–336	Advanced microarchitecture	NOT, 168
Transmission gates, 33. See also	Verilog, 167, 169, 172, 173, 174, 175,	numbers, 180
Transistors	176, 178, 180, 181, 201, 203,	operator precedence, 179
Transmission lines, 534–546	205	OR, 168
reflection coefficient, 544–545	3:8 decoder, 199	parameterized
Z0, 543–544	accessing parts of busses, 189	N:2 <sup>N</sup> decoder, 212
matched termination,	adder, 426	N-bit multiplexer, 211
536–538	ALU decoder, 424	N-input AND gate, 213
mismatched termination,	AND, 168	pattern recognizer
539–541	architecture body, 168	Mealy FSM, 210
open termination, 538–539	assign statement, 168, 197, 178	Moore FSM, 209
proper terminations, 542	asynchronous reset, 192	priority circuit, 201
short termination, 539	bad synchronizer with blocking	RAM, 265
when to use, 41-542	assignments, 206	reg, 191, 194
Tristate buffer, 70–71	bit swizzling, 182	register, 191
Truth tables, 55, 56, 60, 61, 177	blocking assignment, 202	register file, 42
ALU decoder, 376	case sensitivity, 174	resettable flip-flop, 427
"don't care," 77	casez, 201	resettable enabled register, 193
main decoder, 376, 379	combinational logic, 168, 202	resettable register, 192
multiplexer, 79	comments, 174	ROM, 266
seven-segment display decoder, 76	comparators, 242	self-checking testbench, 215
SR latch, 106	continuous assignment statement,	seven-segment display decoder,
with undefined and floating inputs,	173	198
181	controller, 423	shift register, 256
TSOP. See Thin small outline	counter, 254	sign extension, 427
package	datapath, 425	single-cycle MIPS processor,
TTL. See Transistor-Transistor Logic	datapath, 423 default, 198	422
Two-level logic, 65–66		STD_LOGIC, 168, 183
Two's complement numbers, 16–18.	divide-by-3 finite state machine,	
	207, 208	statement, 173 structural models
See also Binary numbers	D latch, 195	structurai models

2:1 multiplexer, 188	MIPS testbench, 429	pages, 485
4:1 multiplexer, 187	MIPS top-level module, 430	page faults, 485
subtractor, 241	multiplexers, 175, 176, 428	page offset, 486–488
synchronizer, 194	multiplier, 247	page table, 488–489
synchronous reset, 192	numbers, 180	multilevel page tables, 492–494
testbench, 214	operand, 173	replacement policies, 492
with test vector file, 216	operator precedence, 179	translation lookaside buffer (TLB),
tristate buffer, 180	others, 198	490. See Translation looka-
truth tables with undefined and	parameterized	side buffer
floating inputs, 181	N-bit multiplexer, 211	write policies, 482–483
type declaration, 168	N-input AND gate, 213	Virtual pages, 485
wires, 178	N:2 <sup>N</sup> decoder, 212	Virtual page number, 487
VHDL libraries and types, 167, 169,	pattern recognizer	Volatile memory, 259. See also DRAM,
172, 173, 174, 175, 176, 178,	Mealy FSM, 210	SRAM, Flip-flops
180, 181, 183–185, 203, 205	Moore FSM, 209	Voltage, threshold, 29
3:8 decoder, 199	priority circuit, 201	$V_{SS}$ , 23
accessing parts of busses, 189	process, 191	
adder, 426	RAM, 265	
architecture, 187	register, 191	W
asynchronous reset, 192	register file, 426	
bad synchronizer with blocking	resettable enabled register, 193	
assignments, 206	resettable flip-flop, 427	W. f 20
bit swizzling, 182	resettable register, 192	Wafers, 28
boolean, 183	RISING_EDGE, 191	Wall, Larry, 20 WAR. See Write after read
case sensitivity, 174	ROM, 266	
clk'event, 191	selected signal assignment state-	WAW. See Write after write
combinational logic, 168	ments, 176	White space 174
comments, 174	self-checking testbench, 215	White space, 174
comparators, 242	seven-segment display decoder, 198	Whitmore, Georgiana, 7 Wire, 63
concurrent signal assignment, 173,	shift register, 256	Word-addressable memory, 295
178	sign extension, 427	Write policies, 482–483
controller, 423	signals, 178, 194	Write after read (WAR) hazard, 442.
CONV_STD_LOGIC_VECTOR,	simulation waveforms with delays,	See also Hazards
212	170, 183	Write after write (WAW) hazard,
counter, 254	single-cycle MIPS processor, 422	442–443. See also Hazards
datapath, 425	STD_LOGIC_ARITH, 212	772-775. See uiso Hazards
decoder, 424	structural models	
divide-by-3 finite state machine,	2:1 multiplexer, 188	V
207, 208	4:1 multiplexer, 187	X
D latch, 195	subtractor, 241	
eight-input AND, 174	synchronizer, 194	
expression, 173	synchronous reset, 192	XOR gate, 21
full adder, 178	testbench, 214	XNOR gate, 21
using always/process, 197	with test vector file, 216	Xilinx FPGA, 268
using nonblocking assignments,	tristate buffer, 180	X. See Contention, Don't care.,
204	truth tables with undefined and	
generic statement, 211	floating inputs, 181	
inverters, 172	VHSIC, 169	Z
using always/process, 196	Virtual address, 485–490	<del>-</del>
left shift, 427	Virtual memory, 484–494	
logic gates, 173	address translation, 486–488	7 Car Elandina
with delays, 183	IA-32, 501	Z,. See Floating
main decoder, 424	memory protection, 491	Zero extension, 302