Note: Page numbers in italics indicate figures, tables and text boxes; page numbers preceded by "e" refer to online material.

Acorn RISC Machine, 350	0, 8, 22. See also LOW, FALSE	Acorn Computer Group, 296, 472	Advanced microarchitecture, 456–470
32-bit datapath, 386 32-bit instructions, 329 A/D conversion, 531.e31–531.e32 A/D bor testing, 452 A/D conversion, 531.e31–531.e32 A/D conversion, 531.e31 A/D conversion, 521.e3 A/D conversion, 531.e31 A/D conversion, 52.e A/D converters (A/DCs) A/D converters (A/D converters (A/DCs) A/D conver		1 1,	
32-bit instructions, 329 64-bit architecture, 360 64-bit architecture, 360 74xx series logic, 533.e1–533.e5  2:1 mux (74157), 533.e4 3:8 decoder (74138), 533.e4 4:1 mux (74153), 533.e4 AND (7408), 533.e3 AND (7408), 533.e3 AND (7411), 533.e3 BNAND (7400), 533.e		Active low, 74–75	
64-bit architecture, 360 74xx series logic, 533.e1–533.e5 parts 2:1 mux (74157), 533.e4 3:8 decoder (74138), 533.e4 4:1 mux (74153), 533.e4 AND (7408), 533.e3 AND (7411), 533.e4 BI (15, 15, 15, 15, 15, 15, 15, 15, 15, 15,	* *		1
ADCs. See Analog-to-digital converters parts  (ADCs) ADCs. See Analog-to-digital converters (ADCs) ADCs. See Analog-to-digital converters 2:1 mux (74157), 533.e4 As decoder (74138), 533.e4 At 1 mux (74153), 533.e4 At 1 mux (74153), 533.e3 AND (7408), 533.e3 AND (7408), 533.e3 AND (7401), 533.e3 AND (7421), 533.e3 AND (7421), 533.e3 AND (7402), 533.e3 NAND (7400), 533.e3 NOR (7402), 533.e3 NOR (7432), 533.e3 NOR (7432), 533.e3 Addition, 14-15, 17-18, 235, 239-246, NOT (7404), 533.e3 Addition, 14-15, 17-18, 235, 239-246, NOR (7486), 533.e3 Addition, 14-15, 17-18, 235, 239-246, NOR (7487), 533.e4 Address. See also Adders Finclude, 541.e5-541.e6 Finclude, 541.e6-541.e7. See also Standard libraries  A  ABI. See Application Binary Interface (ABI) ABI. See Application Binary Interface (ABI) ABI. See Application Binary Interface (ABI) Abstraction, 4-5 digital. See Digital abstraction  ADCs. See Analog-to-digital converters (ADCs) ADD. 297, 536 Abders, 239-246 Address, 239-246 Carry-lookahead, 241 ca	64-bit architecture, 360	The state of the s	
parts         (ADCs)         multiprocessors           2:1 mux (74157), 533.e4         ADD, 297, 536         homogeneous multiprocessors. See           3:8 decoder (74138), 533.e4         Adders, 239–246         Homogeneous           4:1 mux (74153), 533.e3         carry propagate, 240         multiprocessors           AND (7408), 533.e3         full, 56, 240         operations           AND4 (7421), 533.e3         half, 240         operations           ANDA (7421), 533.e3         hBL for, 184, 200, 450         multiprocessors. See Multiprocessors           NAND (7400), 533.e3         prefix, 243         out-of-order processor. See Out-of-order processor. See Out-of-order processor. See Nor (7404), 533.e3         addition, 14–15, 17–18, 235, 239–246,         register renaming. See Register           NOR (7402), 533.e3         Addition, 14–15, 17–18, 235, 239–246,         register renaming. See Register           NOR (7432), 533.e3         binary, 14–15         single instruction multiple data. See           register (74377), 533.e4         floating point, 259         Single instruction multiple data. See           Address. See also Memory         superscalar processor. See           #define, 541.e5-541.e6         physical, 509–513         Superscalar processor. See           #define, 541.e5-541.e6         physical, 509–513         Advanced Microontroller Bus           Amemory			
3:8 decoder (74138), 533.e4 4:1 mux (74153), 533.e4 A:1 mux (74153), 533.e4 AND (7408), 533.e3 AND (7408), 533.e3 AND (7411), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 Counter (74161, 74163), 533.e4 FLOP (7474), 533.e1, 533.e3 NAND (7400), 533.e3 NAND (7400), 533.e3 NOR (7402), 533.e3 NOR (7402), 533.e3 NOR (7404), 533.e1 OR (74321), 533.e4 tristate buffer (74244), 533.e4 tristate buffer (74244), 533.e4 XOR (7486), 533.e3  #define, 541.e5-541.e6 #include, 541.e6-541.e7. See also Standard libraries  ABI. See Application Binary Interface (ABI) ABI. See Application Binary Interface (ABI) Abstraction, 4-5 digital. See Digital abstraction  Addders, 239-246 carry propagate, 240 multiprocessors multiprocessors. See Multiprocessors multithreading, See Multithreading out-of-order processor. See Out-of-order processor. See Out-of-order processor register renaming. See Register single instruction multiple data. See Single instruction multiple data. See Single instruction multiple data. See Superscalar processor. See Advanced Microontroller Bus Architecture (AMBA), 531.e54 Advanced High-performance Bus (AHB), 531.e54 ABI. See Application Binary Interface (ABI) Abstraction, 4-5 digital. See Digital abstraction Advanced Micro Devices ALUControl, 248-250, 392, 395	parts		
4:1 mux (74153), 533.e4 AND (7408), 533.e3 AND (7408), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 AND6 (7402), 533.e4 FLOP (7474), 533.e3 NOR (7400), 533.e3 NOR (7401), 533.e3 NOR (7402), 533.e3 NOR (7404), 533.e1 OR (7432), 533.e3 NOR (7482), 533.e4 NOR (7480), 533.e4 NOR (7480), 533.e4 NOR (7480), 533.e5 NOR (7480), 533.e3 NOR (7480), 533.e3 NOR (7480), 533.e3 NOR (7480), 533.e4 NOR (7480), 533.e4 NOR (7480), 533.e3 NOR (7480), 533.e4 NOR (7480), 533.e4 NOR (7480), 533.e4 NOR (7480), 533.e3 NOR (7480), 533.e3 NOR (7480), 533.e4 NOR (7480), 533.e3 NOR (7480), 533.e4 NOR (7480), 533.e3 NOR (7490), 533.e3 NOR (7480), 532.e3 NOR (7480), 533.e3 NOR (7480), 533.e3 NOR (7480), 532.e3 NOR	2:1 mux (74157), 533.e4	ADD, 297, 536	homogeneous multiprocessors. See
AND (7408), 533.e3  AND3 (7411), 533.e3  AND4 (7421), 533.e3  AND4 (7421), 533.e3  AND4 (7421), 533.e3  AND6 (7463), 533.e3  Counter (74161, 74163), 533.e4  FLOP (7474), 533.e1  NOR (7402), 533.e3  NOR (7402), 533.e3  NOR (7402), 533.e3  NOR (7404), 533.e1  OR (74377), 533.e4  register (74377), 533.e4  tristate buffer (74244), 533.e4  XOR (7486), 533.e3  #define, 541.e5–541.e6  #include, 541.e5–541.e6  #include, 541.e5–541.e7. See also  Standard libraries  Addressing modes, ARM, 336  Addressing modes, ARM, 336  Base, 336  immediate, 336  pC-relative, 336  register, 336  Advanced High-performance  Bus (AHB)  Abstraction, 4–5  digital. See Digital abstraction  Advanced Micro Devices  ALUControl, 248–250, 392, 395	3:8 decoder (74138), 533.e4	Adders, 239–246	
AND3 (7411), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 COUNTER (74161, 74163), 533.e4 FLOP (7474), 533.e1, 533.e3 PLOP (7474), 533.e1, 533.e3 PLOP (7474), 533.e1, 533.e3 PLOP (7400), 533.e3 PLOP (7400), 533.e3 PLOP (7400), 533.e3 PLOP (7400), 533.e3 PLOP (7401), 533.e3 PLOP (7401), 533.e3 PLOP (7401), 533.e3 PLOP (7401), 533.e3 PLOP (7402), 533.e3 PLOP (7402), 533.e3 PLOP (7402), 533.e3 PLOP (7404), 533.e1 PLOP (7404), 533.e3 PLOP (7404)	4:1 mux (74153), 533.e4	carry propagate, 240	multiprocessors
AND3 (7411), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 AND4 (7421), 533.e3 COUNTER (74161, 74163), 533.e4 FLOP (7474), 533.e1, 533.e3 PLOP (7474), 533.e1, 533.e3 PLOP (7474), 533.e1, 533.e3 PLOP (7400), 533.e3 PLOP (7400), 533.e3 PLOP (7400), 533.e3 PLOP (7400), 533.e3 PLOP (7401), 533.e3 PLOP (7401), 533.e3 PLOP (7401), 533.e3 PLOP (7401), 533.e3 PLOP (7402), 533.e3 PLOP (7402), 533.e3 PLOP (7402), 533.e3 PLOP (7404), 533.e1 PLOP (7404), 533.e3 PLOP (7404)	AND (7408), 533.e3	carry-lookahead, 241	micro-operations. See Micro-
counter (74161, 74163), 533.e4 FLOP (7474), 533.e1, 533.e3 NAND (7400), 533.e3 NOR (7402), 533.e3 NOR (7402), 533.e3 NOR (7404), 533.e1 NOR (7404), 533.e1 NOR (7404), 533.e1 NOR (7432), 533.e3 NOR (7432), 533.e3 NOR (7437), 533.e4 register (74377), 533.e4 tristate buffer (74244), 533.e4 XOR (7486), 533.e3 Address. See also Memory tristate buffer (74244), 533.e4 XOR (7486), 533.e3 Address. See also Memory superscalar processor. See #include, 541.e5-541.e6 #include, 541.e5-541.e7 Addressing modes, ARM, 336 ABI. See Application Binary Interface (ABI) Abstraction, 4-5 digital. See Digital abstraction Advanced Micro Devices  HIDL for, 184, 200, 450 multithreading. See Multithreading out-of-order processor. See Out-of-order processor register renaming. Such didition, 14-15, 17-18, 235, 239-246, register renaming single instruction multiple data. See Single instruction multiple data. See Single instruction multiple data See Single instruction multiple superscalar processor. See Advanced Microcontroller Bus Advanced Microcontroller Bus Advanced Microcontroller Bus Advanced RISC Machines, Advanced RISC Machines, Advanced High-performance Bus (AHB). Advanced High-performance Bus ALUControl, 248-250, 392, 395	AND3 (7411), 533.e3		operations
FLOP (7474), 533.e1, 533.e3  NAND (7400), 533.e3  NOR (7402), 533.e3  NOT (7404), 533.e1  OR (7432), 533.e3  Pinple-carry, 240  Addition, 14–15, 17–18, 235, 239–246, NOT (7404), 533.e1  297. See also Adders  Pinclude, 541.e5–541.e6  Pinclude, 541.e6–541.e7. See also  Standard libraries  A  A  ABI. See Application Binary Interface (ABI)  Abstraction, 4–5  digital. See Digital abstraction  POR (7474), 533.e3  Addition, 14–15, 17–18, 235, 239–246, Priple-carry, 240  Addition, 14–15, 17–18, 235, 239–246, Prelative, 33.e3  Addition, 14–15, 17–18, 235, 239–246, Prelative, 33.e3  Addition, 14–15, 17–18, 235, 239–246, Prelative, 350  Adders See also Adders  Prefix, 243  Adders Sae, 235  Inaming See Register  renaming.  Standardish. See Also Menory  superscalar processor. See  Advanced Microcontroller Bus  AHB. See Advanced High-performance  Bus (AHB).  A	AND4 (7421), 533.e3	half, 240	multiprocessors. See Multiprocessors
NAND (7400), 533.e3  NOR (7402), 533.e3  NOT (7404), 533.e1  OR (7432), 533.e3  OR (7432), 533.e3  Pipple-carry, 240  Addition, 14–15, 17–18, 235, 239–246,  NOT (7404), 533.e1  OR (7432), 533.e3  Piparty, 14–15  Pipartitiate buffer (74244), 533.e4  Address See also Adders  Pipartitiate buffer (74244), 533.e4  #define, 541.e5–541.e6  #include, 541.e6–541.e7. See also  Standard libraries  Addressing modes, ARM, 336  Addressing modes, ARM, 336  Addressing modes, ARM, 336  Addressing modes, ARM, 336  PC-relative, 336  PC-relative, 336  ABI. See Application Binary Interface (ABI)  Abstraction, 4–5  digital. See Digital abstraction  Addition, 14–15, 17–18, 235, 239–246,  Addition, 14–15, 17–18, 235, 239–246,  register renaming. See Register  reaming  renaming  single instruction multiple data. See  Ada (SIMD)  Address. See also Menory  superscalar processor. See  Advanced Microcontroller Bus  Advanced Micro Devices  Advanced Microcontroller Bus  Architecture (AMBA), 531.e54  Advanced High-performance  Bus (AHB)  AHB-Lite bus, 531.e54–531.e55  Altera FPGA, 274–279  ALU Decoder, 398–400  ALU Decoder, 398–400  ALU Oettrol, 248–250, 392, 395	counter (74161, 74163), 533.e4	HDL for, 184, 200, 450	multithreading. See Multithreading
NOR (7402), 533.e3 NOT (7404), 533.e1 OR (7432), 533.e3 OR (7432), 533.e3 Pregister (74377), 533.e4 Princlude, 541.e5—541.e6 Standard libraries  Addressing modes, ARM, 336 Advanced RISC Machines, Advanced High-performance Bus (AHB) Advanced Micro Devices ALU. See Arithmetic/logical unit (ALU) Advanced Micro Devices ALUControl, 248–250, 392, 395	FLOP (7474), 533.e1, 533.e3	prefix, 243	out-of-order processor. See Out-of-
NOT (7404), 533.e1 OR (7432), 533.e3 binary, 14–15 register (74377), 533.e4 tristate buffer (74244), 533.e4 XOR (7486), 533.e3 XOR (7486), 532.e3 XOR (7486), 533.e3 XOR (7486), 532.e3	NAND (7400), 533.e3	ripple-carry, 240	order processor
OR (7432), 533.e3	NOR (7402), 533.e3	Addition, 14–15, 17–18, 235, 239–246,	register renaming. See Register
register (74377), 533.e4 tristate buffer (74244), 533.e4 XOR (7486), 533.e3  #define, 541.e5–541.e6 #include, 541.e6–541.e7. See also Standard libraries  Standard libraries  A  A  A  A  A  A  A  A  A  A  A  A  A	NOT (7404), 533.e1	297. See also Adders	renaming
tristate buffer (74244), 533.e4 XOR (7486), 533.e3 Address. See also Memory #define, 541.e5–541.e6 #include, 541.e6–541.e7. See also Standard libraries Standard libraries  Addressing modes, ARM, 336 Addressing modes, ARM, 336 Addressing modes, ARM, 336 Addressing modes, ARM, 336 ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction  Addressing binary, 15–17 Address. See also Memory superscalar processor Advanced Microcontroller Bus Advanced RISC Machines, Advanced RISC Machines, Advanced RISC Machines, Advanced High-performance Bus (AHB) AHB. See Advanced High-performance Advanced RISC Machines, Advanced High-performance Bus ALU. See Arithmetic/logical unit (ALU) Advanced Micro Devices ALUControl, 248–250, 392, 395	OR (7432), 533.e3	binary, 14–15	single instruction multiple data. See
XOR (7486), 533.e3 Address. See also Memory #define, 541.e5–541.e6 physical, 509–513 Superscalar processor #include, 541.e6–541.e7. See also translation, 509–512 Advanced Microcontroller Bus Standard libraries Virtual, 508. See also Virtual memory Advanced RISC Machines, Addressing modes, ARM, 336 Addressing modes, ARM, 336 AHB. See Advanced High-performance immediate, 336 Bus (AHB) PC-relative, 336 register, 336 ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction Address. See also Memory superscalar processor. See Advanced Microcontroller Bus Advanced RISC Machines, Advanced RISC Machines, AHB- See Advanced High-performance Bus ALU. See Arithmetic/logical unit (ALU) ALU Decoder, 398–400 ALU Decoder, 398–400 ALU Decoder, 398–400 ALU Decoder, 392, 395	register (74377), 533.e4	floating point, 259	Single instruction multiple
#define, 541.e5–541.e6 physical, 509–513 Superscalar processor #include, 541.e6–541.e7. See also translation, 509–512 Advanced Microcontroller Bus Standard libraries virtual, 508. See also Virtual memory Advanced RISC Machines, Addressing modes, ARM, 336 472  ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction Advanced Micro Devices physical, 509–513 Superscalar processor Advanced Microcontroller Bus Advanced RISC Machines, Advanced RISC Machines, Advanced High-performance Bus (AHB) AHB. See Advanced High-performance Bus Advanced High-performance Bus ALU. See Arithmetic/logical unit (ALU) Advanced Micro Devices ALUControl, 248–250, 392, 395	tristate buffer (74244), 533.e4	signed binary, 15-17	data (SIMD)
#include, 541.e6–541.e7. See also translation, 509–512 Advanced Microcontroller Bus virtual, 508. See also Virtual Architecture (AMBA), 531.e54  Addressing modes, ARM, 336 472  Addressing modes, ARM, 336 472  AHB. See Advanced High-performance immediate, 336 Bus (AHB)  PC-relative, 336 Altera FPGA, 274–279  ABI. See Application Binary Interface (ABI) Abstraction, 4–5 (AHB), 531.e54  digital. See Digital abstraction Advanced Micro Devices ALUControl, 248–250, 392, 395	XOR (7486), 533.e3	Address. See also Memory	superscalar processor. See
Standard libraries  Virtual, 508. See also Virtual memory Addressing modes, ARM, 336 Addressing modes, ARM, 336 Addressing modes, ARM, 336 AHB. See Advanced High-performance immediate, 336 PC-relative, 336 ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction  Virtual, 508. See also Virtual Advanced RISC Machines, AHB. See Advanced High-performance Bus (AHB) AHB. See Advanced High-performance Bus ALU. See Arithmetic/logical unit (ALU) Advanced Micro Devices ALUControl, 248–250, 392, 395	#define, 541.e5-541.e6	physical, 509-513	Superscalar processor
Memory Addressing modes, ARM, 336 472  Addressing modes, ARM, 336 472  AHB. See Advanced High-performance immediate, 336 Bus (AHB)  PC-relative, 336 AHB-Lite bus, 531.e54–531.e55  register, 336 Altera FPGA, 274–279  ABI. See Application Binary Interface (ABI) Advanced High-performance Bus Abstraction, 4–5 (AHB), 531.e54 ALU Decoder, 398–400  Advanced Micro Devices ALUControl, 248–250, 392, 395	#include, 541.e6-541.e7. See also	translation, 509-512	Advanced Microcontroller Bus
Addressing modes, ARM, 336  base, 336  immediate, 336  PC-relative, 336  ABI. See Application Binary Interface (ABI)  Abstraction, 4–5  digital. See Digital abstraction  Addressing modes, ARM, 336  Bus (AHB)  AHB-Lite bus, 531.e54–531.e55  Altera FPGA, 274–279  Advanced High-performance Bus  ALU. See Arithmetic/logical unit (ALU)  ALU Decoder, 398–400  ALU Ontrol, 248–250, 392, 395	Standard libraries	virtual, 508. See also Virtual	Architecture (AMBA), 531.e54
base, 336 immediate, 336 PC-relative, 336 ABI. See Advanced High-performance Bus (AHB) AHB-Lite bus, 531.e54–531.e55 register, 336 Altera FPGA, 274–279 Advanced High-performance Bus Abstraction, 4–5 (AHB), 531.e54 Alture Application Binary Interface (ABI) Abstraction, 4–5 (AHB), 531.e54 ALU Decoder, 398–400		memory	Advanced RISC Machines,
immediate, 336 PC-relative, 336 AHB-Lite bus, 531.e54–531.e55 register, 336 Altera FPGA, 274–279 ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction Advanced Micro Devices Bus (AHB) AHB-Lite bus, 531.e54 Altera FPGA, 274–279 ALU. See Arithmetic/logical unit (ALU) ALU Decoder, 398–400 ALUControl, 248–250, 392, 395		Addressing modes, ARM, 336	472
PC-relative, 336 AHB-Lite bus, 531.e54–531.e55 register, 336 ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction Advanced Micro Devices ALU. See Arithmetic/logical unit (ALU) ALU Decoder, 398–400	Α.	base, 336	AHB. See Advanced High-performance
register, 336 Altera FPGA, 274–279 ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction  register, 336 Altera FPGA, 274–279 ALU. See Arithmetic/logical unit (ALU) ALU Decoder, 398–400 Advanced Micro Devices ALUControl, 248–250, 392, 395	A	immediate, 336	Bus (AHB)
ABI. See Application Binary Interface (ABI) Abstraction, 4–5 digital. See Digital abstraction  Advanced High-performance Bus (AHB), 531.e54 ALU Decoder, 398–400 Advanced Micro Devices  ALUControl, 248–250, 392, 395		,	AHB-Lite bus, 531.e54–531.e55
Abstraction, 4–5 (AHB), 531.e54 ALU Decoder, 398–400 digital. See Digital abstraction Advanced Micro Devices ALUControl, 248–250, 392, 395		ě ,	
digital. See Digital abstraction Advanced Micro Devices ALUControl, 248-250, 392, 395			. ,
, , , , , , , , , , , , , , , , , , , ,			
Accumulator, 367 (AMD), 296 ALUOp, 398	digital. See Digital abstraction		
	Accumulator, 367	(AMD), 296	ALUOp, 398

ALUResult, 392–397	power-saving and security	SIMD instructions, 358-360
ALUSrc, 396	instructions, 358	Thumb instruction set, 351–352
AMAT. See Average memory access time	SIMD instructions, 358–360	ARM instructions, 295–369, 535–540
(AMAT)	Thumb instruction set, 351–352	branch instructions, 308–309, 539
AMBA. See Advanced Microcontroller	machine language, 329	condition flags, 306-308, 540
Bus Architecture (AMBA)	addressing modes, 336	data-processing instructions,
AMD. See Advanced Micro Devices (AMD)	branch instructions, 334–335	303–306, 535–537
AMD64, 368	data-processing instructions,	logical instructions, 303–304
Amdahl, Gene, 492	329–333	multiply instructions, 305-306,
Amdahl's Law, 492	interpreting, 336–337	537
American Standard Code for	memory instructions, 333–334	shift instructions, 304–305
Information Interchange	stored program, 337-338	formats
(ASCII), 315–316, 541.e8, 541.	odds and ends, 345	addressing modes, 336
e27-541.e28	exceptions, 347–350	branch instructions, 334
Analog I/O, 531.e25-531.e32	loading literals, 345-346	data-processing instructions,
A/D conversion, 531.e31–531.e32	NOP, 346	329–333
D/A conversion, 531.e25–531.e28	programming, 303	interpreting, 336–337
Pulse-width modulation (PWM),	branching, 308-309	memory instructions, 333–335
531.e28-531.e31	conditional statements, 309-312	stored program, 337-338
Analog-to-digital converters (ADCs),	condition flags, 306-308	instruction set, 295
531.e25, 531.e27, 531.e31–531.	function calls, 317-329	memory instructions, 301–303,
e32	getting loopy, 312-313	313–317, 538
Analytical engine, 7–8	logical and arithmetic	miscellaneous instructions, 345-346,
AND gate, 20–22, 179	instructions, 303–306	539
chips (7408, 7411, 7421), 533.e3	memory, 313–317	ARM Microcontroller Development Kit
truth table, 20, 22	x86 architecture, 360	(MDK-ARM), 297
using CMOS transistors, 32-33	big picture, 368	ARM microprocessor, 385
AND, 303-304	instruction encoding, 364-367	data memory, 385-388
AND-OR (AO) gate, 46	instructions, 364	instruction memory, 385-388
Anode, 27	operands, 362–363	multicycle, 406–425
Antidependence, 464	peculiarities, 367–368	pipelined, 425–433
Application Binary Interface (ABI), 320	registers, 362	program counter, 385-388
Application-specific integrated circuits	status flags, 363-364	register file, 385–388
(ASICs), 533.e9	Arguments, 317–319, 541.e15	single-cycle, 390-406, 443-456
Architectural state, 338, 364	pass by reference, 541.e22	state elements of, 385–388
for ARM, 385–386	pass by value, 541.e22	ARM processors, 470
Architecture, 295	Arithmetic	ARM registers, 299–300
assembly language, 296	ARM instructions, 303-306	program counter, 308, 338, 386–387
instructions, 297–298	circuits, 239–255	register file, 386–387
operands, 298–303	C operators, 541.e11–541.e13	register set, 299–300
compiling, assembling, and loading,	HDL operators, 185	ARM single-cycle HDL, 443–456
339	Arithmetic/logical unit (ALU), 248-251,	building blocks, 449-452
assembling, 342-343	392	controller, 443
compilation, 340–341	implementation of, 249	datapath, 443
linking, 343–344	in processor, 392–430	testbench, 452–456
loading, 344–345	ARM architecture, evolution of, 296,	ARM7, 472, 473
memory map, 339–340	350	ARM9, 474
evolution of ARM architecture, 350	64-bit architecture, 360	ARM9E, 472
64-bit architecture, 360	digital signal processing (DSP)	ARMv3 architecture, 472
digital signal processors (DSPs),	instructions, 352–356	ARMv4 instruction set, 295, 539
352–356	floating-point instructions, 357–358	ARMv7 instruction, 472
floating-point instructions,	power-saving and security	Arrays, 313–317, 541.e23–541.e29
357–358	instructions, 358	accessing, 313–317, 541,e23

bytes and characters, 315–317, 541. e27–541.e29	Behavioral modeling, 173–174 Benchmarks, 389	Bluetooth wireless communication, 531. e42–531.e43
comparison or assignment of, 541.e28	BEQ, 309	BlueSMiRF silver module, 531.
declaration, 314-317, 541.e23	Biased exponent, 257	e42-531.e43
indexing, 314-317, 541.e23-541.e27	BIC (bit clear), 303-304	classes, 531.e42
initialization, 541.e23-541.e24	big.LITTLE, 469	BNE, 310
as input argument, 541.e24-541.e25	Big-endian memory, 303	Boole, George, 8
multi-dimension, 541.e26-541.e27	Big-endian order, 178	Boolean algebra, 60-66
ASCII. See American Standard Code for	Binary addition, 14-15. See also Adders,	axioms, 61
Information Interchange (ASCII)	Addition	equation simplification, 65-66
ASICs. See Application-specific	Binary coded decimal (BCD),	theorems, 61–64
integrated circuits (ASICs)	258	Boolean equations, 58–60
ASR, 304	Binary encoding, 125-126, 129-131	product-of-sums form,
Assembler, 339, 541.e44	for divide-by-3 counter, 129-131	60
Assembling, 342–343	for traffic light FSM, 125-126	sum-of-products form, 58-60
Assembly language, ARM, 295-350,	Binary numbers	Boolean logic, 8. See also Boolean
535-540	signed, 15–19	algebra, Logic gates
instructions, 297-350, 535-540	unsigned, 9–11	Boolean theorems, 61–64
operands, 297-303	Binary to decimal conversion, 10,	associativity, 63
translating high-level code to, 339-345	10–11	combining, 62
translating machine language to, 337	Binary to hexadecimal conversion, 12	commutativity, 63
Assembly language, x86. See x86	Bipolar junction transistors, 26	complements, 62
Associativity	Bipolar motor drive, 531.e50	consensus, 62, 64
in Boolean algebra, 62, 63	Bipolar signaling, 531.e18	covering, 62
in caches, 493, 498-500	Bipolar stepper motor, 531.e51, 531.	De Morgan's, 63-64
Astable circuits, 119	e52–531.e53	distributivity, 63
Asymmetric multiprocessors. See	AIRPAX LB82773-M1, 531.e51,	idempotency, 62
Heterogeneous multiprocessors	531.e51	identity, 62
Asynchronous circuits, 120-123	direct drive current, 531.e52	involution, 62
Asynchronous resettable flip-flops	Bistable element, 109	null element, 62
definition, 116	Bit, 8	Branch if less than (BLT), 334–335
HDL, 194–196	dirty, 506	Branch instructions, 308–309
Asynchronous serial link, 531.e17, 531.	least significant, 13, 14	ARM instructions, 539, 539
e17. See also Universal	most significant, 13, 14	Branch misprediction penalty, 438,
Asynchronous Receiver	sign, 16	459
Transmitter (UART)	use, 502	Branch prediction, 459-461
AT Attachment (ATA), 531.e61–531.e62	valid, 496	Branch target address (BTA), 334-335
Average memory access time (AMAT),	Bit cells, 264–269	Branch target buffer, 459
491, 504	DRAM, 266–267	Branching, 308–309, 334–336
	ROM, 268–270	conditional, 309
D	SRAM, 267	unconditional, 309
В	Bit swizzling, 188	Breadboards, 533.e18-533.e19
	Bitline, 264	BTA. See Branch target address (BTA)
	Bitwise operators, 177–179	Bubble, 20, 63
В, 308–309, 334–336, 396–397	BL (branch and link), 318	pushing, 63–64, 71–73
Babbage, Charles, 7	Block, 493	Bubble, in pipeline, 435–436
Banked registers, 348–349	Block offset, 500-501	Buffers, 20
Base addressing, 336	Block size (b), 493, 500–501	lack of, 117
Baud rate, 531.e17–531.e19	Blocking and nonblocking assignments,	tristate, 74–75
BCD. See Binary coded decimal (BCD)	199–200, 205–209	Bugs, 175
BCM2835, 531.e3, 531.e4–531.e5, 531.	BLT. See Branch if less than (BLT)	in C code, 541.e45–541.e49
e8, 531.e9, 531.e19	BlueSMiRF silver module, 531.e42–531.	Bus, 56
timer, 531.e23	e43, 531.e42	tristate, 75

Bus interfaces, 531.e54–531.e57	parameters	Character LCDs, 531.e33–531.e36
AHB-Lite, 531.e54–531.e55	block, 493	Characters (char), 315-317, 541.e8,
memory and peripheral	block size, 493, 500-501	541.e27
interface example, 531.	capacity (C), 492–493	arrays. See also Strings
e55–531.e57	degree of associativity (N), 499	C type, 541.e27
Bypassing, 432. See also Forwarding	number of sets (S), 493	Chips, 28
Byte, 13-14, 315-317. See also	performance of	multiprocessors, 468
Characters	hit, 490–492	Chopper constant current drive, 531.e51
least significant, 13-14	hit rate, 491–492	Circuits
most significant, 13–14	miss, 480–492, 505	74xx series. See 74xx series logic
Byte offset, 495	capacity, 505	application-specific integrated
Byte-addressable memory, 301–302	compulsory, 505	(ASICs), 533.e9
big-endian, 302–303	conflict, 498, 505	astable, 119
little-endian, 303	penalty, 500	asynchronous, 120, 122–123
nene enam, occ	miss rate, 491–492	combinational. See Combinational
	reducing, 505–506	logic
	miss rate vs. cache parameters,	definition of, 55
C	505–506	delay, 88–92
	replacement policy, 502–503	glitches in, 92–95
	status bits	multiple-output, 68
C programming, 541.e1–541.e49	dirty bit (D), 506	priority, 68
common mistakes. See Common	use bit $(U)$ , 502	sequential. See Sequential logic
mistakes in C	valid bit (V), 496	synchronous, 122–123
compiler. See Compiler,	write policy, 506–507	synchronous sequential, 120–123
i_Hlt414277118n C	write-back, 506–507	synthesized, 176, 179, 181
conditional statements. See		timing, 88–95, 141–151
Conditional statements	write-through, 506–507	,
control-flow statements. See Control-	CAD. See Computer-aided design (CAD)	CISC. See Complex Instruction Set
flow statements	Callee, 317	Computer (CISC) architectures
	Callee save rule, 324	CLBs. See Configurable logic blocks
data types. See Data types	Callee-saved registers, 323	(CLBs)
executing a program, 541.e4	Caller save rule, 324	Clock cycles per instruction (CPI), 390
function calls. See Function calls	Caller-saved registers, 323	Clock period, 142, 390
loops. See Loops	Canonical form. See Sum-of-products	Clock skew, 148–151
operators. See Operators	(SOP) form, Product-of-sums	Clustered multiprocessors, 470
simple program, 541.e3–541.e4	(POS) form	cmd field, 330, 535, 537
standard libraries. See Standard	Capacitors, 28	CMOS. See Complementary Metal-
libraries	Capacity, of cache, 492–493	Oxide-Semiconductor Logic
variables. See Variables in C	Capacity miss, 505	(CMOS)
Caches, 489–508	Carry propagate adder (CPA). See Carry-	CMP, 402
address fields	lookahead adder (CLA); Prefix	Combinational composition, 56
block offset, 500–501	adders; Ripple-carry adder	Combinational logic, 174
byte offset, 495	Carry-lookahead adder (CLA),	design, 55–106
set bits, 495	241–243, 242	Boolean algebra, 60–66
tag, 495	case statement, in HDL, 201–203.	Boolean equations, 58–60
advanced design, 503-507	See also Switch/case statement	building blocks, 83–88, 239–255
evolution of, in ARM, 507	casez, case?, in HDL, 205	delays, 88–92
multiple level, 504	Cathode, 27	don't cares, 81–82
organizations, 502	Cathode ray tube (CRT), 531.e36.	Karnaugh maps (K-maps), 75–83
direct mapped, 494–498	See also VGA (Video Graphics	multilevel, 66–73
fully associative, 499–500	Array) monitor	precedence, 58
multi-way set associative,	horizontal blanking interval, 531.e36	timing, 88–95
498–499	vertical blanking interval, 531.e36	two-level, 69

X (contention). So (X)	ee Contention	Conditional signal assignments, 181–182	CPI. See Clock cycles per instruction (CPI); Cycles per instruction (CPI)
X (don't cares). S (X)	ee Don't care	Conditional statements, 309 in ARM assembly	Critical path, 89–92, 402 Cross-coupled inverters, 109, 110
Z (floating). See 1	Floating (Z)	if, 309–310	bistable operation of, 110
HDLs. See Hardward	0 , ,	if/else, 310-311	CRT. See Cathode ray tube (CRT)
languages (HI		switch/case, 311-312	Current Program Status Register
Combining theorem, 62	,	in C, 541.e17–541.e18	(CPSR), 306, 324, 347
Command line argumen		if, 541.e17-541.e18	Cycle time. See Clock period
e44-541.e45	,	if/else, <b>541.e17</b>	Cycles per instruction (CPI), 390, 424
Comments		switch/case, 541.e17-541.e18	Cyclic paths, 120
in ARM assembly, 2	.97–298	in HDL, 194, 201–205	Cyclone IV FPGA, 275–279
in C, 297-298, 541.	e5	case, 201-203	
in SystemVerilog, 18	0	casez, case?, 205	
in VHDL, 180		if, if/else, 202-205	D.
Common mistakes in C,	541.e45–541.	Configurable logic blocks (CLBs), 275,	D
e49		533.e7. See also Logic elements	
Comparators, 246–248		(LEs)	
Comparison		Conflict miss, 505	D flip-flops. See Flip-flops
in hardware. See Con		Consensus theorem, 62, 64	D latch. See La_Hlt414277505tches
	gical unit (ALU)	Constants	D/A conversion, 531.e25–531.e28
processor performan	ce, 424–423	in ARM assembly, 300–301. See also	e e
using ALU, 251	5 541 04 541	Immediates in C, 541.e5–541.e6	(DACs) DAQs. See Data Acquisition Systems
Compiler, in C, 339–34 e5, 541.e43–541.		Contamination delay, 88–92. See also	(DAQs)
Complementary Metal-C		Short path	Data Acquisition Systems (DAQs), 531.
Semiconductor ga		Contention (x), 73–74	e62–531.e63
26–34	1100/,	Context switching, 467	myDAQ, 531.e62–531.e63
Complements theorem,	62	Continuous assignment statements, 179	
Complex instruction set		193, 200, 206	HDL for, 455
(CISC) architectu		Control hazard, 432, 437-440	Data memory, 387-388
458		Control signals, 91, 249	Data segment, 340
Complexity managemen	t, 4–7	Control unit, 386. See also ALU	Data sheets, 533.e9-533.e14
digital abstraction, 4	-5	Decoder, Main Decoder	Data types, 541.e21–541.e35
discipline, 5–6		of multicycle ARM processor,	arrays. See Arrays
hierarchy, 6–7		413–423	characters. See Characters (char)
modularity, 6–7		of pipelined ARM processor,	dynamic memory allocation. See
regularity, 6–7		430	Dynamic memory allocation
Compulsory miss, 505	(CAD) 74	of single-cycle ARM processor,	(malloc, free)
Computer-aided design	(CAD), /1,	397–401	linked list. See Linked list
129 Concurrent signal assign	una cunt	Control-flow statements conditional statements. See	pointers. See Pointers strings. See Strings
0 0		Conditional statements	structures. See Structures (struct)
statement, 179, 1 200–206	103–104, 173,	loops. See Loops	typedef, 541.e31–541.e32
cond field, 306–307, 33	0 535	CoreMark, 389	Datapath
Condition flags, 306–30		Cortex-A7 and -A15, 475	multicycle ARM processor, 406–413
ARM instructions, 5		Cortex-A9, 475	B instruction, 412–413
Condition mnemonics,	*	Counters, 260–261	LDR instruction, 407–410
Conditional assignment,		divide-by-3, 130	STR instruction, 411–412
Conditional branches, 3		Covering theorem, 62	pipelined ARM processor, 428-430
Conditional Logic, 398-		CPA. See Carry propagate	single-cycle ARM processor, 390
Conditional operator, 1	81–182	adder (CPA)	B instruction, 396–397

Datapath (Continued)	application-specific integrated circuits	Dynamic data segment, 340
LDR instruction, 391–394	(ASICs), 533.e9	Dynamic discipline, 142-151. See also
STR instruction, 394–396	assembly of, 533.e17-533.e20	Timing analysis
Data-processing instructions, 536	breadboards, 533.e18-533.e19	Dynamic memory allocation (malloc,
ARM instructions, 329–333,	data sheets, 533.e9-533.e14	free), 541.e32-541.e33
396–397, 535–537	economics, 533.e33-533.e35	in ARM memory map, 340
encodings, 536	logic families, 533.e15-533.e17	Dynamic power, 34
DC motors, 531.e43, 531.e44–531.e48	packaging, 533.e17-533.e20	Dynamic random access memory
H-bridge, 531.e44, 531.e45	printed circuit boards, 533.e19-533.	(DRAM), 266–267, 487–490,
shaft encoder, 531.e43-531.e44	e20	519, 531.e58, 531.e60, 531.e61
DC transfer characteristics, 24-26.	programmable logic, 533.e2-533.e9	
See also Direct current (DC)	Digital-to-analog converters (DACs),	
transfer characteristics, Noise	531.e25–531.e28	E.
margins	DIMM. See Dual inline memory module	E
DDR. See Double-data rate memory	(DIMM)	
(DDR)	Diodes, 27–28	
De Morgan, Augustus, 63	p-n junction, 28	EasyPIO, 531.e6
De Morgan's theorem, 63-64	DIPs. See Dual-inline packages (DIPs)	Economics, 533.e33
DE-9 cable, 531.e19	Direct current (DC) transfer	Edge-triggered flip-flop. See Flip-flops
Decimal numbers, 9	characteristics, 24, 25	EEPROM. See Electrically erasable
Decimal to binary conversion, 11	Direct mapped cache, 494-498, 495	programmable read only memory
Decimal to hexadecimal conversion, 13	Direct voltage drive, 531.e51	(EEPROM)
Decode stage, 425	Dirty bit (D), 506	EFLAGS register, 363
Decoders	Discipline	Electrically erasable programmable read
definition of, 86–87	dynamic, 142-151. See also Timing	only memory (EEPROM), 270
HDL for	analysis	Embedded I/O (input/output) systems,
behavioral, 202–203	static, 142-151. See also Noise	531.e3–531.e32
parameterized, 219	margins	analog I/O, 531.e25-531.e32
logic using, 87–88	Discrete-valued variables, 7	A/D conversion, 531.e31–531.
Seven-segment. See Seven-segment	Distributivity theorem, 63	e32
display decoder	Divide-by-3 counter	D/A conversion, 531.e25–531.
Deep pipelines, 457	design of, 129–131	e28
Delaymicros function, 531.e24	HDL for, 210–211	digital I/O, 531.e8–531.e11
Delays, logic gates. See also Propagation	Divider, 254–255	general-purpose I/O (GPIO), 531.
delay	Division	e8–531.e11
in HDL (simulation only), 188–189	circuits, 254–255	interrupts, 531.e32
DeleteUser function, 541.e33	Do/while loops, in C, 541.e19-541.e20	LCDs. See Liquid Crystal Displays
Dennard, Robert, 266	Don't care (X), 69, 81–83, 205	(LCDs)
Destination register (rd or rt), 393, 409	Dopant atoms, 27	microcontroller peripherals, 531.
Device driver, 531.e3, 531.e6–531.e8	Double, C type, 541.e8–541.e9	e32–531.e53
Device under test (DUT), 220	Double-data rate memory (DDR), 268,	motors. See Motors
Dhrystone, 389	531.e60–531.e61	serial I/O, 531.e11–531.e23. See also
Dice, 28	Double-precision formats, 258	Serial I/O
Dielectric, 28	DRAM. See Dynamic random access	timers, 531.e23–531.e24
Digital abstraction, 4–5, 7–9, 22–26	memory (DRAM)	VGA monitor. See VGA (Video
Digital circuits. See Logic	DSPs. See Digital signal processors	Graphics Array) monitor
Digital signal processors (DSPs),	(DSPs)	Enabled flip-flops, 115–116
352–356, 469	Dual inline memory module (DIMM),	Enabled registers, 196–197. See also
Digital system implementation, 533.	531.e60	Flip-flops
e1–533.e35	Dual-inline packages (DIPs), 28, 533.e1,	EOR (XOR), 303–304
74xx series logic. See 74xx series	533.e17	EPROM. See Erasable programmable
logic	Dynamic branch predictors, 459	read only memory (EPROM)

Equality comparator, 247	snail/pattern recognizer FSM,	Format conversion (atoi, atol, atof),
Equation minimization	132–134, 212–213	541.e41–541.e42
using Boolean algebra, 65–66	state encodings, 129–131. See also	Forwarding, 432–435. See also Hazards
using Karnaugh maps. See Karnaugh	Binary encoding,	FPGAs. See Field programmable gate
maps (K-maps)	One-cold encoding, One-hot	arrays (FPGAs)
Erasable programmable read only	encoding	FPU. See Floating-point unit (FPU)
memory (EPROM), 270, 533.e6	state transition diagram, 124, 125	FPSCR. See Floating-Point Status and
Ethernet, 531.e61	traffic light FSM, 123–129	Control Register (FPSCR)
Exceptions, 346–350	Fixed-point numbers, 255–256	Frequency shift keying (FSK), 531.e42
banked registers, 348–349	Flags, 250	and GFSK waveforms, 531.e42
exception-related instructions,	Flash memory, 270. See also Solid state	Front porch, 531.e37
349–350	drive (SSD)	FSK. See Frequency shift keying (FSK)
exception vector table, 347–348	Flip-flops, 114–118, 193–197. See also	FSMs. See Finite state machines (FSMs)
execution modes and privilege	Registers	Full adder, 56, 182, 184, 200, 240
levels, 347	back-to-back, 145, 152-157, 197.	using always/process statement, 200
handler, 340, 349	See also Synchronizers	Fully associative cache, 499–500
start-up, 350	comparison with latches, 118	funct field, 330, 333
Execution time, 389	enabled, 115-116	Function calls, 317, 541.e15–541.e16
exit, 541.e41	HDL for, 451. See also Registers	additional arguments and local
Extended instruction pointer (EIP), 362	metastable state of. See Metastability	variables, 328–329
ExtImm, 408	register, 114–115	arguments, 319, 541.e15
	resettable, 116	leaf, 324–326
	scannable, 262–263	multiple registers, loading and
F	shift register, 261–263	storing, 322
г	transistor count, 114, 117	naming conventions, 541.e16
	transistor-level, 116–117	with no inputs or outputs, 318,
	Float, C type, 541.e6-541.e9	541.e15
factorial function call, 326	print formats of, 541.e36–541.e37	nonleaf, 324–326
stack during, 327	Floating (Z), 74–75	preserved registers, 322–324
Factoring state machines, 134–136	in HDLs, 186–188	prototypes, 541.e16
False, 8, 20, 35, 58, 60, 74, 111, 112,	Floating output node, 117	recursive, 326–328
113, 116, 124, 196	Floating point division (FDIV) bug,	return, 318–319, 541.e15
Fast Fourier Transform (FFT), 352	175	stack, use of, 320–322. See also Stack
FDIV. See Floating-point division (FDIV)	Floating-gate transistor, 270. See also	Furber, Steve, 473
FFT. See Fast Fourier Transform (FFT)	Flash memory	Fuse-programmable ROM, 269–270
Field programmable gate arrays	Floating-point division (FDIV), 259	
(FPGAs), 274–279, 531.e14,	Floating-point instructions, ARM,	
531.e38, 531.e63, 533.e7–533.e9	357–358	G
driving VGA cable, 531.e38	Floating-point numbers, 256–258	u
in SPI interface, 531.e13–531.e16	addition, 259	
File manipulation, in C, 541.e38–541.	formats, single- and double-	
e40	precision, 258	Gates
Finite state machines (FSMs), 123–141,	in programming. See Double, C type;	AND, 20, 22, 128
209–213, 413, 417	Float, C type	buffer, 20
complete multicycle control, 424	rounding, 259	multiple-input, 21–22
deriving from circuit, 137–140	special cases	NAND, 21, 31
divide-by-3 FSM, 129–131, 210–211	infinity, 258	NOR, 21–22, 111, 128
factoring, 134–136, 136	NaN, 258	NOT, 20
in HDL, 209–213	Floating-Point Status and Control	OR, 21
LE configuration for, 277–279	Register (FPSCR), 358	transistor-level. See Transistors
Mealy FSM, 132–134	Floating-point unit (FPU), 259	XNOR, 21
Moore FSM, 132–134	For loops, 312–313, 541.e20	XOR, 21

General-purpose I/O (GPIO), 531.	parameterized modules, 217–220	Homogeneous multiprocessors,
e8–531.e11	processor building blocks, 449–452	468–469
switches and LEDs example, 531.e8	register file, 450	Hopper, Grace, 340
Generate signal, 241, 243	resettable flip-flop, 451	
Genwaves function, 531.e27	resettable flip-flop with enable, 452	
Glitches, 92–95	sequential logic, 193–198, 209–213	T. Control of the Con
Global data segment, 340	simulation and synthesis, 175–177	•
GPIO. See General-purpose I/O (GPIO)	single-cycle ARM processor,	
Graphics accelerators, 469	443–456	MO See Leavelle to the (MO)
Graphics processing units (GPUs), 460	structural modeling, 190–193	I/O. See Input/output (I/O) systems
Gray, Frank, 76	testbench, 220–224, 452–453	IA-32 architecture. See x86
Gray codes, 76	top-level module, 454	IA-64, 368
Ground (GND), 22	Hardware handshaking, 531.e18	ICs. See Integrated circuits (ICs)
symbol for, 31	Hardware reduction, 70–71. See also	Idempotency theorem, 62
	Equation minimization	Identity theorem, 62
	Hazard unit, 432–435	Idioms, 177
H	Hazards. See also Hazard unit	if statements
••	control hazards, 432, 437–440	in ARM assembly, 309–310
	data hazards, 432–436	in C, 541.e17
II 16 11 240 240	pipelined processor, 431–441	in HDL, 202–205
Half adder, 240, 240	read after write (RAW), 431, 464	if/else statements, 310, 541.e27
Hard disk, 490–491. See also Hard	solving	in ARM assembly, 310–311
drive	control hazards, 437–440	in C, 541.e17–541.e18
Hard drive, 490, 508. See also Hard	forwarding, 432–434	in HDL, 202–205
disk, Solid state drive (SSD),	stalls, 435–436	ILP. See Instruction level parallelism (ILP)
Virtual memory	write after read (WAR), 464	IM. See Instruction memory
Hardware description languages	write after write (WAW), 465	imm8 field, 330-331
(HDLs), 443–456. See also	H-bridge control, 531.e45	<i>imm</i> 12 field, 333
SystemVerilog, VHSIC Hardware	HDL. See Hardware description	<i>imm</i> 24 field, 334
Description Language (VHDL)	languages (HDLs), SystemVerilog;	Immediate addressing, 336
2:1 multiplexer, 452	VHSIC Hardware Description	Immediate extension, 451
adder, 450	Language (VHDL)	Immediates, 300–301, 330–332,
capacity, 505	Heap, 340	345–346. See also Constants
combinational logic, 174, 198	Heterogeneous multiprocessors,	Implicit leading one, 257
bitwise operators, 177–179	469–470	Information, amount of, 8
blocking and nonblocking	Hexadecimal numbers, 11–13	Initializing
assignments, 205–209	Hexadecimal to binary and decimal	arrays in C, 541.e23–541.e24
case statements, 201–202	conversion, 11, 12	variables in C, 541.e11
conditional assignment, 181–182	Hierarchy, 6	Input/Output (I/O) systems, 531.
delays, 188–189	HIGH, 23. See also 1, ON	e1–531.e64
data memory, 455	High-level programming languages,	device driver, 531.e3, 531.e6–531.e8
data types, 213–217	303, 541.e2	embedded I/O systems. See
history of, 174–175	compiling, assembling, and loading,	Embedded I/O (input/output)
if statements, 202–205	339–345	systems
internal variables, 182–184	translating into assembly, 300	I/O registers, 531.e3
numbers, 185	High-performance microprocessors, 456	memory-mapped I/O, 531.e1–531.e3
operators and precedence,	Hit, 490	personal computer I/O systems. See
184–185	Hit rate, 491	Personal computer (PC) I/O systems
reduction operators, 180–181 immediate extension, <i>451</i>	Hold time constraint, 142–148 with clock skew, 149–151	Input/output elements (IOEs), 275
instruction memory, 455–456	Hold time violations, 145, 146,	Institute of Electrical and Electronics
modules, 173–174	147–148, 150–151	Engineers (IEEE), 257–258

Instruction encoding, x86, 364-367,	K	Linked list, 541.e33-541.e34
366		Linker, 340–341
Instruction formats, ARM, 328		Linking, 339
addressing modes, 336	Karnaugh, Maurice, 75	Linux, 531.e23–531.e24
branch instructions, 334–335	Karnaugh maps (K-maps), 75–84,	Liquid crystal displays (LCDs),
data-processing instructions, 329–333	93–95, 126	531.e33–531.e36
interpreting, 336–337	logic minimization using, 77–83	Literal, 58, 96
memory instructions, 333–335	prime implicants, 65, 77–81, 94–95	loading, 345–346
stored program, 337–338	seven-segment display decoder, 79–81	Little-endian bus order in HDL, 178
Instruction formats, x86, 364–367	with "don't cares", 81–82	Little-endian memory addressing, 303
Instruction level parallelism (ILP), 465,	Kilobit (Kb/Kbit), 14	Load register instruction (LDR), 301–302
467, 468	Kilobyte (KB), 14	Loading literals, 345–346
Instruction memory, 387, 427, 455	K-maps. See Karnaugh maps (K-maps)	Loads, 344–345
Instruction register (IR), 407, 414		base addressing of, 336
Instruction set, 295		Local variables, 328–329
for ARM, 386	L	Locality, 488
Instruction set. See also Architecture	_	Logic
Instructions, x86, 360–368		bubble pushing, 71–73 combinational. See Combinational
Instructions, ARM, 295–360, 535–540 branch instructions, 308–309, 539	LAB. See Logic array block (LAB)	logic
condition flags, 306–308, 540	Land grid array, 531.e58	families, 25–26, 533.e15–533.e17,
data-processing instructions, 535	Language. See also Instructions	533.e15, 533.e17
logical, 303–304, 536–537	assembly, 296–303	gates. See Gates
memory instructions, 301–303,	machine, 329–338	hardware reduction, 70–71
313–317, 333–334, 538	mnemonic, 297	multilevel. See Multilevel
miscellaneous instructions, 539	Last-in-first-out (LIFO) queue, 320.	combinational logic
multiply instructions, 305–306, 537	See also Stack	programmable, 533.e2–533.e9
shift instructions, 304–305	Latches, 111–113	sequential. See Sequential logic
Instructions per cycle (IPC), 390	comparison with flip-flops, 109, 118	transistor-level. See Transistors
Integrated circuits (ICs), 533.e17	D, 113, 120	two-level, 69
Intel. See x86	SR, 111–113, 112	Logic array block (LAB), 276
Intel processors, 360	transistor-level, 116–117	Logic arrays, 271-280. See also Field
Intel x86. See x86	Latency, 157–160, 425, 435	programmable gate arrays
Interrupts, 347, 531.e32	Lattice, silicon, 27	(FPGAs), Programmable logic
Invalid logic level, 186	LCDs. See Liquid crystal displays (LCDs)	arrays (PLAs)
Inverters, 20, 119, 178. See also NOT	LDR, 301–303, 313–317, 333–334,	transistor-level implementation,
gate	391–394, 538	279–280
cross-coupled, 109, 110	critical paths for, 402	Logic elements (LEs), 275–279
in HDL, 178, 199  An Investigation of the Laws of Thought	Leaf function, 324 Leakage current, 34	of Cyclone IV, 276–277
(Boole), 8	Least recently used (LRU) replacement,	functions built using, 277–279 Logic families, 25–26, 533.e15–533.e17,
Involution theorem, 62	502–503	533.e15, 533.e17
IOEs. See Input/output elements (IOEs)	two-way associative cache with,	compatibility of, 26
IPC. See Instructions per cycle (IPC)	502–503, 503	logic levels of, 25
IR. See Instruction register (IR)	Least significant bit (lsb), 13, 14	specifications, 533.e15, 533.e17
IRWrite, 407, 414	Least significant byte (LSB), 13, 14, 301	Logic gates, 19–22, 179, 533.e2
,	LEs. See Logic elements (LEs)	AND. See AND gate
	Level-sensitive latch. See	AND-OR (AO) gate, 46
J	La_Hlt414277542tches: D	with delays in HDL, 189
	LIFO. See Last-in-first-out (LIFO) queue	multiple-input gates, 21-22
	Line options, compiler and command,	NAND. See NAND gate
Java, 303. See also Language	341–343, 541.e43–541.e45	NOR. See NOR gate

Logic gates (Continued)	Magnitude comparator, 247	Memory and peripheral interface, 531.
NOT. See NOT gate	Main Decoder, 398-400, 400	e55–531.e57
OR. See OR gate	Main FSM, 413–423, 423	Memory arrays, 264-271. See also
OR-AND-INVERT (OAI) gate, 46	main function in C, 541.e3	Memory
XNOR. See XNOR gate	Main memory, 489-491	bit cell, 264-270
XOR. See XOR gate	malloc function, 541.e32	HDL for, 272, 273, 455–456
Logic levels, 22–26	Mantissa, 257	logic using, 270–271
Logic simulation, 175-176	Master-slave flip-flop. See Flip-flops	organization, 264-265
Logic synthesis, 176–177, 176	Masuoka, Fujio, 270	Memory hierarchy, 490-491
Logical instructions, 303–304	math.h, C library, 541.e42-541.e43	Memory instructions, 301–303,
Logical shifter, 251	Max-delay constraint. See Setup time	313–317, 333–334, 391–394
Lookup tables (LUTs), 270, 275–276	constraint	encodings, 333–334, 538
Loops, 312–313, 541.e19–541.e20	Maxterms, 58	Memory interface, 487–488
in ARM assembly	MCUs. See Microcontroller units	Memory map, ARM, 339–340, 531.e2
for, 312-313	(MCUs)	Memory performance. See Average
while, 312	Mealy machines, 123, 123, 132-134	Memory Access Time (AMAT)
in C	state transition and output table, 134	Memory protection, 515
do/while, 541.e19-541.e20	state transition diagrams, 133	Memory systems, 487
for, 541.e20	timing diagrams for, 135	ARM, 507–508
while, 541.e19	Mean time between failure (MTBF),	performance analysis, 491-492
Lovelace, Ada, 338	153–154	x86, 531.e3
LOW, 23. See also 0, FALSE	Medium-scale integration (MSI) chips,	Memory-mapped I/O, 531.e1-531.e3,
Low Voltage CMOS Logic (LVCMOS),	533.e2	531.e7
25	MemWrite, 394, 397	address decoder, 531.e1, 531.e2
Low Voltage TTL Logic (LVTTL), 25	Memory, 313. See also Memory arrays	communicating with I/O devices,
lsb. See Least significant bit (lsb)	access time, 491	531.e2
LSB. See Least significant byte (LSB)	addressing modes, 363	hardware, 531.e2, 531.e2, 531.e3
LSL, 304	area and delay, 267–268	MemtoReg, 396, 397
LSR, 304	big-endian, 302	Metal-oxide-semiconductor field
LUTs. See Lookup tables (LUTs)	byte-addressable, 301–303	effect transistors (MOSFETs),
LVCMOS. See Low Voltage CMOS	bytes and characters, 315–317	26
Logic (LVCMOS)	HDL for, 272, 273, 455–456	switch models of, 30
LVTTL. See Low Voltage TTL Logic	hierarchy, 490	Metastability, 151–157
(LVTTL)	little-endian, 303	metastable state, 110, 151
(= ·)	logic using, 270–271	resolution time, 151–152, 154–157
	main, 490	synchronizers, 152–154
	operands in, 301–303	Microarchitecture, 296, 385, 388–389.
M	physical, 509	See also Architecture
	ports, 265–266	advanced. See Advanced
	protection, 515. See also Virtual	microarchitecture
MAC. See Multiply-accumulate (MAC)	memory	architectural state. See Architectural
Machine code. See Machine language	types, 266–270	state
Machine language, 329	DDR, 268	description of, 385–389
addressing modes, 336	DRAM, 266–267	design process, 386–388
branch instructions, 334–335	flash, 270	evolution of, 470–476
data-processing instructions,	register file, 268	HDL representation, 443–456
329–333	ROM, 268–270	generic building blocks,
interpreting, 336–337	SRAM, 266	449–452
memory instructions, 333–335	virtual, 490. See also Virtual	single-cycle processor, 444–449
stored program, 337–338, 338	memory	testbench, 452–456
translating to assembly language,	Memory address computation, 419	multicycle processor. See Multicycle
337	data flow during, 419	ARM processor
557	add non during, 117	That processor

performance analysis, 389–390.  See also Performance analysis pipelined processor. See Pipelined  ARM processor real-world perspective, 470–476 single-cycle processor. See Single- cycle ARM processor Microcontroller, 531.e3, 531.e25 Microcontroller peripherals, 531. e32–531.e53 Bluetooth wireless communication, 531.e42–531.e43 character LCD, 531.e33–531.e36 control, 531.e35–531.e36 parallel interface, 531.e33	Moore's law, 30 MOS transistors. See Metal-oxide- semiconductor field effect transistors (MOSFETs) MOSFET. See Metal-oxide- semiconductor field effect transistors (MOSFETs) Most significant bit (msb), 13, 14 Most significant byte (MSB), 13, 14, 301, 302 Motors DC, 531.e43, 531.e44–531.e47 H-bridge, 531.e45–531.e46, 531. e45, 531.e46 servo, 531.e44, 531.e48–531.e49	Multiply and multiply-accumulate instructions, 355–356  Multiply-accumulate (MAC), 352, 356  Multiply-accumulate (MAC), 352, 356  Multiprocessors, 468–470     chip, 468     heterogeneous, 469–470     homogeneous, 468  Multi-Protocol Synchronous Serial Engine (MPSSE), 531.e63  Multithreaded processor, 467  Multithreading, 467–468  Mux. See Multiplexers myDAQ, 531.e62–531.e63
motor control, 531.e43–531.e53	stepper, 531.e44, 531.e49–531.e53	N
VGA monitor, 531.e36–531.e42 Microcontroller units (MCUs), 531.e3 Micro-operations (micro-ops), 458–459	MOV, 301 MPSSE. See Multi-Protocol Synchronous Serial Engine (MPSSE)	NAND (7400), 533.e3
designers, 456	msb. See Most significant bit (msb)	NAND gate, 21
high-performance, 456	MSB. See Most significant byte (MSB)	CMOS, 31–32
Microprocessors, 3, 13, 295 architectural state of, 338	MSI chips. See Medium-scale integration (MSI) chips	Nested if/else statement, 311, 541.e18 Newton computer, 472
Millions of instructions per	MTBF. See Mean time between failure	Nibbles, 13–14
second, 425	(MTBF)	nMOS transistors, 28–31, 29–30
Min-delay constraint. See Hold time constraint	Multicycle ARM processor, 406 control, 413–421	Noise margins, 23–26, 23 calculating, 23–24
Minterms, 58	datapath, 407-413	Nonarchitectural state, 386, 388
Miss, 490–492, 505	B instruction, 412–413	Nonblocking and blocking assignments,
capacity, 505	data-processing instructions, 412	199–200, 205–209
compulsory, 505	LDR instruction, 407–410	Nonleaf function calls, 324–326
conflict, 498, 505	STR instruction, 411–412	Nonpreserved registers, 322–323, 326
Miss penalty, 500 Miss rate, 491–492	performance, 421–425 Multicycle microarchitectures, 388	NOP, 346, 431 NOR gate, 21–22, 63, 533.e3
and access times, 492	Multilevel combinational logic, 69–73.	chip (7402), 533.e3
Misses	See also Logic	CMOS, 32
cache, 490	Multilevel page tables, 516–518	pseudo-nMOS logic, 33
capacity, 505	Multiple-output circuit, 68-69	truth table, 22
compulsory, 505	Multiplexers, 83–86	Not a number (NaN), 258
conflict, 505	definition of, 83–84	NOT gate, 20
page fault, 509–510	HDL for	chip (7404), 533.e3
Modularity, 6	behavioral model of, 181–183 parameterized N-bit, 218–219	CMOS, 31 Noyce, Robert, 26
Modules, in HDL	structural model of, 190–193	Null element theorem, 62
behavioral and structural, 173–174	logic using, 84–86	Number conversion
parameterized modules, 217-220	symbol and truth table, 83	binary to decimal, 10-11
Moore, Gordon, 30	Multiplicand, 252–253	binary to hexadecimal, 12
Moore machines, 123, 132	Multiplication. See Multiplier	decimal to binary, 11, 13
state transition and output	Multiplier, 252–253	decimal to hexadecimal, 13
table, 134	HDL for, 253	hexadecimal to binary and decimal,
state transition diagrams, 133 timing diagrams for, 135	Multiply instructions, 305–306, 537, 537	11, 12 taking the two's complement, 16
dining diagrams 101, 133	337	taking the two s complement, 10

Number systems, 9–19	ORR (OR), 303-304	Personal computer (PC) I/O systems,
binary, 9–11, 10–11	OTP. See One-time programmable	531.e57–531.e64
comparison of, 18-19, 19	(OTP)	data acquisition systems, 531.
estimating powers of two, 14	Out-of-order execution, 466	e62–531.e63
fixed-point, 255, 255–256	Out-of-order processor, 463–465	DDR3 memory, 531.e60–531.e61
floating-point, 256–259	Output dependence, 465	networking, 531.e61
addition, 259, 260	Overflow	PCI, 531.e59–531.e60
special cases, 258	with addition, 15	SATA, 531.e61–531.e62
hexadecimal, 11–13, 12	detection, 250–251	USB, 531.e59, 531.e63–531.e64
negative and positive, 15	Oxide, 28	Phase locked loop (PLL), 531.e39
sign/magnitude, 15–16		Physical memory, 509
signed, 15–18	P	Physical page number (PPN), 511
two's complement, 16–18	•	Physical pages, 509
unsigned, 9–11		Pipelined ARM processor, 425–428
		abstract view of, 427
	Packages, chips, 533.e17–533.e18	control unit, 430
0	Page fault, 509	datapath, 428–429
0	Page number, 511	description, 425-428
	Page offset, 511	hazards, 431-441
	Page table, 510–513	performance analysis, 441-443
Odds and ends, 345	Pages, 509	throughput, 426
exceptions, 346–350	Paging, 516	Pipelined microarchitecture. See
loading literals, 345–346	Parallel I/O, 531.e11	Pipelined ARM processor
NOP, 346	Parallelism, 157–160	Pipelining, 158–160
OFF, 26, 30	Parity gate. See XOR gate	PLAs. See Programmable logic arrays
Offset, 302, 392, 408	Partial products, 252	(PLAs)
Offset indexing, ARM, 314	Pass by reference, 541.e22	Plastic leaded chip carriers (PLCCs),
ON, 26, 30	Pass by value, 541.e22	533.e17
One-bit dynamic branch predictor, 460	Pass gate. See Transmission gates	Platters, 508
One-cold encoding, 130	PC. See Program counter (PC)	PLCCs. See Plastic leaded chip carriers
One-hot encoding, 129–131	PC Logic, 400	(PLCCs)
One-time programmable (OTP), 533.e2	PCB. See Printed circuit boards (PCBs)	PLDs. See Programmable logic devices
op field, 330	PCI. See Peripheral Component	(PLDs)
Opcode. See op field	Interconnect (PCI)	PLL. See Phase locked loop (PLL)
Operands	* ,	
*	PCI express (PCIe), 531.e60	pMOS transistors, 28–31, 29
ARM, 298	PC-relative addressing, 335, 336	Pointers, 541.e21–541.e23, 541.e25,
constants/immediates, 300–301	PCSrc, 394, 395–396, 440	541.e28, 541.e30, 541.e32
memory, 301–303	PCWrite, 410	POS. See Product-of-sums (POS) form
registers, 299	Perfect induction, proving theorems	Positive edge-triggered flip-flop, 114
register set, 300	using, 64–65	Post-indexed addressing, ARM, 314
x86, 362–363, 363	Performance analysis, 389–390	Power consumption, 34–35
Operation code. See op field	multicycle ARM processor, 422–424	Power-saving and security instructions,
Operators	pipelined ARM processor, 425–428	358
in C, 541.e11–541.e14	processor comparison, 424	PPN. See Physical page number (PPN)
in HDL, 177–185	single-cycle ARM processor, 402	Prefix adders, 243–245, 244
bitwise, 177–181	Performance Analysis, 389–390.	Prefix tree, 245
precedence, 185	See also Average Memory Access	Pre-indexed addressing, ARM, 314
reduction, 180–181	Time (AMAT)	Preserved registers, 322–324, 323
table of, 185	Peripheral Component Interconnect	Prime implicants, 65, 77
ternary, 181–182	(PCI), 531.e59–531.e60	Printed circuit boards (PCBs), 533.
OR gate, 21	Peripherals devices. See Input/output	e19-533.e20
OR-AND-INVERT (OAI) gate, 46	(I/O) systems	printf, 541.e35-541.e37

Priority circuit, 68–69	Q	Resettable flip-flops, 116
encoder, 102–103, 105		Resettable registers, 194–196 Resolution time, 151–152. <i>See also</i>
Procedure calls. See Function calls	Quiescent supply current, 34	Metastability
Processor performance comparison, 442	Quiescent supply current, 51	derivation of, 154–157
multicycle ARM processor, 424		Return value, 317 RF. See Register file (RF)
pipelined ARM processor, 442 single-cycle processor, 405	R	Ring oscillator, 119, 119
Processor-memory gap, 489		Ripple-carry adder, 240, 240–241, 243
Product-of-sums (POS) form, 60		RISC architecture. See Reduced
Program counter (PC), 308, 338, 387,	Race conditions, 119-120, 120	instruction set computer (RISC)
394	rand, 541.e40–541.e41	architecture
Programmable logic arrays (PLAs), 67,	Random access memory (RAM),	Rising edge, 88
272–274, 533.e6–533.e7 transistor-level implementation, 280	266–268, 271, 272 Raspberry Pi, 531.e3–531.e4, 531.e5,	Rm field, 330 Rn field, 330
Programmable logic devices (PLDs),	531.e6, 531.e32, 531.e48–531.	ROM. See Read only memory (ROM)
533.e6	e49	ROR, 304
Programmable read only memories	RAW hazard. See Read after write	rot field, 330-331
(PROMs), 269, 271, 533.e2–533.	(RAW) hazard	Rotations per minute (RPM), 531.e44
e6	Rd field, 330	Rotators, 251–252
Programming in ARM, 303	Read after write (RAW) hazard, 431, 464. See also Hazards	Rounding modes, 259 RPM. See Rotations per minute (RPM)
arrays. See Arrays	Read only memory (ROM), 266,	RS-232, 531.e18
branching. See Branching	268–270	,
in C. See C programming	transistor-level implementation,	S
conditional statements, 309–312	279–280	3
condition flags, 306–308	Read/write head, 508	
constants. See Constants; Immediates function calls. See Function calls	ReadData bus, 393, 394 Receiver gate, 22	Sampling, 141
getting loopy, 312–313	Recursive function calls, 326–328	Sampling rate, 531.e25
logical and arithmetic instructions,	Reduced instruction set computer (RISC)	SATA. See Serial ATA (SATA)
303–306	architecture, 298, 458	Saturated arithmetic, 353
loops. See Loops	Reduction operators, 180–181	Scalar processor, 461–463, 460
memory, 313–317	Register file (RF)	Scan chains, 262–263
shift instructions, 304–305 PROMs. See Programmable read only	ARM register descriptions, 299 HDL for, 449	scanf, 541.e38 Scannable flip-flop, 262–263
memories (PROMs)	in pipelined ARM processor (write on	Schematics, rules of drawing, 31, 67
Propagate signal, 241	falling edge), 428	SCK. See Serial Clock (SCK)
Propagation delay, 88-92. See also	schematic, 268	SDI. See Serial Data In (SDI)
Critical path	use in ARM processor, 387	SDO. See Serial Data Out (SDO)
Pseudoinstructions, 346	Register renaming, 465–467	SDRAM. See Synchronous dynamic random access memory (SDRAM)
Pseudo-nMOS logic, 33–34, 33 NOR gate, 33	Register set, 300. See also Register file (RF)	Segment descriptor, 367
ROMs and PLAs, 279–280	Registers. See ARM registers; Flip-flops;	Segmentation, 367
Pulse-Width Modulation (PWM), 531.	x86 registers	Selected signal assignment statements,
e28–531.e31	loading and storing, 322	182
analog output with, 531.e30–531.	preserved and nonpreserved,	Semiconductors, 27
e31	322–324 RagSrc 402	industry, sales, 3 Sequencing overhead, 143–144, 149,
duty cycle, 531.e28 signal, 531.e28	RegSrc, 402 Regularity, 6	160, 442
PWM. See Pulse-Width Modulation	RegWrite, 393, 433	Sequential building blocks. See
(PWM)	Replacement policies, 516	Sequential logic

	outs to a m	1 ( 222 222
Sequential logic, 109–161, 259–263	Silicon lattice, 27	stack frame, 322, 328
counters, 260	SIMD. See Single instruction multiple	stack pointer (SP), 320
finite state machines. See Finite state	data (SIMD)	storing additional arguments on,
machines (FSMs)	SIMD instructions, 358–360	328–329
flip-flops, 114–118. See also	simple function, 318	storing local variables on, 328–329
Registers	Simple programmable logic devices	Stalls, 435–436. See also Hazards
latches, 111–113	(SPLDs), 274	Standard libraries, 541.e35–541.e43
D, 113	Simulation waveforms, 176	math, 541.e42–541.e43
SR, 111–113	with delays, 189	stdio, 541.e35–541.e40
registers. See Registers shift registers, 261–263	Single instruction multiple data (SIMD), 460, 472	file manipulation, 541.e38–541.
timing of. See Timing analysis	Single-cycle ARM processor, 390, 444	printf, 541.e35-541.e37
Serial ATA (SATA), 531.e62	Conditional Logic, 447–448	scanf, 541.e38
Serial Clock (SCK), 531.e12	control, 397–401	stdlib, 541.e40-541.e42
Serial communication, with PC, 531.e20	controller, 445	exit, 541.e41
Serial Data In (SDI), 531.e12	datapath, 390, 448-449	format conversion (atoi, atol,
Serial Data Out (SDO), 531.e12	B instruction, 396–397	atof), 541.e41-541.e42
Serial I/O, 531.e11–531.e23	data-processing instructions,	rand, srand, 541.e40-541.e41
SPI. See Serial peripheral interface	395–396	string, 541.e43
(SPI)	LDR instruction, 391–394	State encodings, FSM, 129–131, 134.
UART. See Universal Asynchronous	STR instruction, 394–396	See also Binary encoding, One-
Receiver Transmitter (UART)	Decoder, 446	cold encoding, One-hot encoding
Serial Peripheral Interface (SPI), 531.	instructions, 402	State machine circuit. See Finite state
e11, 531.e12–531.e17	performance, 402–405	machines (FSMs)
connection between PI and FPGA,	Single-cycle microarchitecture, 388	State variables, 109
531.e14	Single-precision formats, 258. See also	Static branch prediction, 459
ports	Floating-point numbers	Static discipline, 24–26
Serial Clock (SCK), 531.e12	Skew. See Clock skew	Static power, 34
Serial Data In (SDI), 531.e12	Slash notation, 56	Static random access memory (SRAM),
Serial Data Out (SDO), 531.e12	Slave latch, 114. See also Flip-flops	266, 267, 519
register fields in, 531.e13	Small-scale integration (SSI) chips, 533.	Status flags, 363. See also Condition
slave circuitry and timing, 531.e15	e2	flags
waveforms, 531.e12	Solid state drive (SSD), 490. See also	stdio.h, C library, 541.e35-541.e40.
Servo motor, 531.e44, 531.e48–531.e49	Flash memory, Hard drive	See also Standard libraries
Set bits, 495	SOP. See Sum-of-products (SOP) form	stdlib.h, C library, 541.e40-541.e42.
Setup time constraint, 142, 145–147	Spatial locality, 488, 500–502	See also Standard libraries
with clock skew, 148-150	Spatial parallelism, 157–158	Stepper motors, 531.e44, 531.e49–531.
Seven-segment display decoder, 79–82	SPEC, 389	e53
with don't cares, 82-83	SPECINT2000, 424	bipolar stepper motor, 531.e49, 531.
HDL for, 201–202	SPI. See Serial Peripheral Interface (SPI)	e50–531.e52
Shaft encoder, 531.e43, 531.e47–531.	Squashing, 465	half-step drive, 531.e50, 531.e51
e48, 531.e48	SR latches, 111–113, 112	two-phase-on drive, 531.e50,
Shift instructions, 304–305, 305	SRAM. See Static random access	531.e51
Shift registers, 261–263	memory (SRAM)	wave drive, 531.e52–531.e53
Shifters, 251–252	srand, 541.e40-541.e41	Stored program, 337–338
Short path, 89–92	Src2 field, 330, 333	STR, 394–396
Sign bit, 16	SSI chips. See Small-scale integration	string.h, C library, 541.e43
Sign extension, 18	(SSI) chips	Strings, 316–317, 541.e28–541.e29.
Sign/magnitude numbers, 15–16, 256	Stack, 320–329. See also Function calls	See also Characters (char)
Signed binary numbers, 15–19	during recursive function call,	Structural modeling, 173–174,
Signed multiplier, 217	326–328	190–193
Silicon dioxide (SiO <sub>2</sub> ), 28	preserved registers, 322–324	Structures (struct), 541.e29–541.e31

SUB, 297	Moore FSM, 210, 212	Ternary operators, 181, 541.e13
Substrate, 28–29	full adder, 184	Testbench, 452–456
Subtraction, 17, 246, 297	using always/process, 200	Testbenches, HDLs, 220-224
Subtractor, 246–247	using nonblocking assignments,	self-checking, 221–222
Sum-of-products (SOP) form, 58-60	208	simple, 220–221
Superscalar processor, 461–463	history of, 175	with testvectors, 222–224
Supervisor call (SVC) instruction, 349	if statements, 202–205	Text Segment, 340, 344
Supply voltage, 22. See also V <sub>DD</sub>	internal signals, 182–184	Thin small outline package (TSOP), 533.
SVC. See Supervisor call (SVC) instruction	inverters, 178, 199	e17
Swap space, 516	latches, 198	Thread level parallelism (TLP), 467
switch/case statements	logic gates, 177–179	Threshold voltage, 29
in ARM assembly, 311–312	multiplexers, 181–183, 190–193,	Throughput, 157–160, 388, 425, 468
in C, 541.e17-541.e18	218–219	Thumb instruction set, 351–352
in HDL. See case statement, in HDL	multiplier, 217	Timers, 531.e23–531.e24
Symbol table, 342, 343	numbers, 185–186	Timing
Symmetric multiprocessing (SMP), 468.	operators, 185	of combinational logic, 88–95
See also Homogeneous	parameterized modules, 217-220	delay. See Contamination delay;
multiprocessors	$N:2^N$ decoder, 219	Propagation delay
Synchronizers, 152–154, 152–153	N-bit multiplexers, 218–219	glitches. See Glitches
Synchronous circuits, 122-123	N-input AND gate, 220	of sequential logic, 141–157
Synchronous dynamic random access	priority circuit, 204	analysis. See Timing analysis
memory (SDRAM), 268	using don't cares, 205	clock skew. See Clock skew
DDR, 268	reduction operators, 180-181	dynamic discipline, 141-142
Synchronous logic, design, 119-123	registers, 193–197	metastability. See Metastability
Synchronous resettable flip-flops, 116	enabled, 196	resolution time. See Resolution
Synchronous sequential circuits,	resettable, 194–196	time
120-123, 122. See also Finite	sequential logic using, 193-198,	system timing. See Timing
state machines (FSMs)	209–213	analysis
timing specification. See Timing	seven-segment display decoder, 201	Timing analysis, 141–151
analysis	simulation and synthesis, 175-177	calculating cycle time. See Setup time
SystemVerilog, 173–225. See also	structural models, 190–193	constraint
Hardware description languages	synchronizer, 197	with clock skew. See Clock skew
(HDLs)	testbench, 220–224	hold time constraint. See Hold time
accessing parts of busses, 188, 192	self-checking, 222	constraint
bad synchronizer with blocking	simple, 221	max-delay constraint. See Setup time
assignments, 209	with test vector file, 223–224	constraint
bit swizzling, 188	tristate buffer, 187	min-delay constraint. See Hold time
blocking and nonblocking	truth tables with undefined and	constraint
assignment, 199–200,	floating inputs, 187, 188	multicycle processor, 424
205–208	z's and x's, 186-188, 205	pipelined processor, 441
case statements, 201–202, 205		setup time constraint. See Setup time
combinational logic using, 177–193,		constraint
198–208, 217–220	T	single-cycle processor, 405
comments, 180	•	TLB. See Translation lookaside buffer
conditional assignment, 181–182		(TLB)
data types, 213–217	Tag. 405	TLP. See Thread level parallelism (TLP)
decoders, 202–203, 219 delays (in simulation), 189	Tag, 495	Transistors, 26–34
divide-by-3 FSM, 210–211	Taking the two's complement, 16–17 Temporal locality, 488, 493–494, 497,	bipolar, 26
finite state machines (FSMs),	1emporal locality, 488, 493–494, 497, 502	CMOS, 26–33
209–213	Temporal parallelism, 158–159	gates made from, 31–34 latches and flip-flops, 116–117
Mealy FSM, 213	Temporary registers, 299	MOSFETs, 26
ivically 1 olvi, 210	remporary registers, 299	MOSIETS, 20

Transistors (Continued)	TTL. See Transistor-Transistor Logic	Very High Speed Integrated Circuits
nMOS, 28–34, 29–33	(TTL)	(VHSIC), 175. See also VHSIC
pMOS, 28–34, 29–33	Two's complement numbers, 16–18	Hardware Description Language
pseudo-nMOS, 33-34	Two-bit dynamic branch predictor, 460	(VHDL)
ROMs and PLAs, 279-280	Two-cycle latency of LDR, 435	VGA (Video Graphics Array) monitor,
transmission gate, 33	Two-level logic, 69	531.e36–531.e42
Transistor-Transistor Logic (TTL),	typedef, 541.e31-541.e32	connector pinout, 531.e37
25–26, 533.e15–533.e16		driver for, 531.e39-531.e42
Translating and starting a program,		VHDL. See VHSIC Hardware
339		Description Language (VHDL)
Translation lookaside buffer (TLB),	U	VHSIC. See Very High Speed Integrated
514–515		Circuits (VHSIC)
Transmission Control Protocol and		VHSIC Hardware Description Languag
Internet Protocol (TCP/IP), 531.	UART. See Universal Asynchronous	(VHDL), 173–175
e61	Receiver Transmitter (UART)	accessing parts of busses, 188, 192
Transmission gates, 33	Unconditional branches, 308, 309	bad synchronizer with blocking
Transmission lines, 533.e20–533.e33	Undefined instruction exception, 347	assignments, 209
characteristic impedance ( $Z_0$ ), 533.	Unicode, 315	bit swizzling, 188
e30-533.e31	Unit under test (UUT), 220	blocking and nonblocking assignment,
derivation of, 533.e30-533.e31	Unity gain points, 24	199–200, 205–208
matched termination, 533.e22-533.	Universal Asynchronous Receiver	case statements, 201–202, 205
e24	Transmitter (UART), 531.	combinational logic using, 177-193
mismatched termination, 533.	e17-531.e23	198–208, 217–220
e25-533.e28	hardware handshaking, 531.e18	comments, 180
open termination, 533.e24–533.e25	Universal Serial Bus (USB), 270, 531.	conditional assignment, 181-182
reflection coefficient $(k_r)$ , 533.	e18, 531.e59	data types, 213–217
e31–533.e32	USB 1.0, 531.e59	decoders, 202-203, 219
derivation of, 533.e31-533.e32	USB 2.0, 531.e59	delays (in simulation), 189
series and parallel terminations, 533.	USB 3.0, 531.e59	divide-by-3 FSM, 210-211
e28–533.e30	Unsigned multiplier, 217, 252-253	finite state machines (FSMs),
short termination, 533.e25	Unsigned numbers, 18	209–213
when to use, 533.e28	Upton, Eben, 531.e4	Mealy FSM, 213
Transparent latch. See Latches: D	USB. See Universal Serial Bus (USB)	Moore FSM, 210, 212
Traps, 347	USB links, 531.e63–531.e64	full adder, 184
Tristate buffer, 74–75, 187	FTDI, 531.e63	using always/process, 200
HDL for, 186–187	UM232H module, 531.e64	using nonblocking assignments,
multiplexer built using, 84-85,	Use bit $(U)$ , 502	208
91–93	( //	history of, 175
True, 8, 20–22, 58–59, 70, 74,		if statements, 202
111–112, 116, 129, 176, 180,		internal signals, 182–184
205	V	inverters, 178, 199
Truth tables, 20		latches, 198
ALU decoder, 399, 404		logic gates, 177–179
with don't cares, 69, 81–83, 205	Valid bit (V), 496	multiplexer, 181–183, 190–193,
multiplexer, 83	Variables in C, 541.e7–541.e11	218–219
seven-segment display decoder, 79	global and local, 541.e9–541.e10	multiplier, 217
SR latch, 111, 112	initializing, 541.e11	numbers, 185–186
with undefined and floating inputs,	primitive data types, 541.e8–541.e9	operators, 185
187–188	$V_{CC}$ , 23. See also Supply voltage, $V_{DD}$	parameterized modules, 217–220
TSOP. See Thin small outline package	$V_{DD}$ , 22, 23. See also Supply voltage	$N:2^N$ decoder, 219
(TSOP)	Vector processor, 460	N-bit multiplexers, 218, 219
(/	Verilog. See SystemVerilog	N-input AND gate, 220, 220
	-0,	

priority circuit, 204 reduction operators, 180–181 using don't cares, 205 reduction operators, 180–181 registers, 193–197 enabled, 196 resettable, 194–196 sequential logic using, 193–198, 209–213	replacement policies, 516 translation lookaside buffer (TLB), 514–515 write policy, 506–507 Virtual page number (VPN), 512 Virtual pages, 509 Vss, 23	Write after read (WAR) hazard, 464.  See also Hazards  Write after write (WAW) hazard, 464-465  Write policy, 506-507 write-back, 506-507 write-through, 506-507
seven-segment display decoder,	W	X
simulation and synthesis, 175–177		
structural models, 190–193 synchronizer, 197 testbench, 220–224 self-checking, 222 simple, 221 with test vector file, 223–224 tristate buffer, 187 truth tables with undefined and floating inputs, 187, 188 z's and x's, 186–188, 205 Video Graphics Array (VGA). See VGA (Video Graphics Array) monitor Virtual address, 509 space, 515	Wafers, 28 Wait for event (WFE) instruction, 358 Wait for interrupt (WFI) instruction, 358 Wall, Larry, 20 WAR hazard. See Write after read (WAR) hazard WAW hazard. See Write after write (WAW) hazard Weak pull-up, 33 Weird number, 18 WFE. See Wait for event (WFE) instruction WFI. See Wait for interrupt (WFI)	X. See Contention (x); Don't care (X) x86  architecture, 360–368, 362 big picture, 368 branch conditions, 366 instruction encoding, 364–367 instructions, 364–367 memory addressing modes, 363 operands, 362–363 peculiarities, 368 registers, 362 status flags, 363
Virtual memory, 490, 508–518 address translation, 509–512 cache terms comparison, 510 memory protection, 515 multilevel page tables, 516–518 page fault, 509–510 page number, 511 page offset, 511 pages, 509 page table, 512–513	instruction while loops, 312, 541.e19 White space, 180 Whitmore, Georgiana, 7 Wi-Fi, 531.e61 Wilson, Sophie, 472 Wire, 67 Wireless communication, Bluetooth, 531.e42–531.e43 Wordline, 264	Xilinx FPGA, 275 XNOR gate, 21–22 XOR gate, 21  Z. See Floating (Z)