## INDEX

## Symbols

\& (AND, Verilog), 42
= or := (blocking assignment), 22, 214
\# (delay, Verilog), 76, 128
\%f (formatter), 233
<, > (comparison), 122
\{\} (concatenation, Verilog), 101
\& (concatenation, VHDL), 101
<= (non-blocking assignment), 54, 214
| (OR, Verilog), 42
<< (shift left, Verilog), 225
>> (shift right, Verilog), 226
? (ternary operator, Verilog), 93, 178
^(XOR, Verilog), 42

## A

Actel, 3, 5
addition, 215-219, 232
Alchitry Cu, 257
almost empty (AE), 118, 145
almost full (AF), 118, 145
Altera, 3, 16, 69
ALU (arithmetic logic unit), 197
always block, 53, 57
one vs. two, 149-157
AMD, 3, 16, 46, 64, 69, 87, 144, 188-189, 197, 246, 256
analog-to-digital converter (ADC), 5, 191, 195, 240
AND gate, 32, 40-42, 54, 58, 71
and keyword, 42
application-specific integrated circuits (ASICs), 7-8, 89
arbiter, 127, 228
architecture keyword, 22
Arduino, 5, 16, 257
arithmetic logic unit (ALU), 197
artificial intelligence (AI), 4

ASCII, 97-98
assertions, 84
assert keyword, 85-86, 128, 157
assign keyword, 22
assignment operators
blocking (=, :=), 22, 214
non-blocking (<=), 54, 214
Atmel. See Microchip Technology

## B

bandwidth, 6, 249
bank (pins), 242
bidirectional pin, 240
binary, 33, 162
Binary_To_7Segment module, 161, 169
Bitcoin, 8
black box, 68
block RAM, 115-116, 186, 188, 191-194
creation, 193
error detection and correction, 193
features and limitations, 192
initializing, 128, 193
instantiation template, 186
precalculated table, 227
size, 192
Boolean algebra, 31-32, 36-40
on FPGA, 39
order of operations, 36
symbols, 36
bouncing of switch, 75
BRAM. See block RAM
buffers, 238-239, 246, 253
bugs, 67, 89, 117

## C

career tips, 259-267
case statement, 152-153, 164, 172
clock data recovery (CDR), 251-253
clocks, 47
constraints, 131
counting cycles, $77,80,96,102$, 108, 182
creation via PLL, 199-204
crossing domains, 141-146
reference, 200
skew, 249-251
\$clog2() function, 80, 114
coding style, 78. See also naming convention
combinational logic, 57-59, 122
concatenation, 101, 107
constraints, 54-55, 131, 145-146
Coordinate Rotation Digital Computer
(CORDIC), 229
cores, 185
core voltage, 32
counter
LFSR, 102
signed, 206
traditional, 107
traditional vs. LFSR, 110
wraparound, 208
cyclic redundancy check (CRC), 35

## D

datasheets, 63
data types, 206-209
converting, 210-211
data valid (DV) signal, 112
DC balance, 251-253
debounce filter, 76
debouncing of switch, 75-84, 161, 169
debugging, 87-88
decimals, 33, 230
delay, 50, 61, 73, 96. See also propagation delay
De Morgan's law, 40
demultiplexer (demux), 92, 94-95, 106
depth, 112, 114
development board, 14, 255-259
device under test (DUT), 70
D flip-flop (DFF), 46, 64
Diamond Programmer, 14-15, 20
installation, 18
programming, 26-28
differential signaling, 243-245

Digilent, 16, 257
digital signal processing (DSP), 194. See also DSP block
\$display() function, 128
division, 225-228
done pulse, 103, 105, 107
double-flopping, 141-142
double rate data (DDR), 245
drive strength, 242-243
DSP block, 194, 229
analog vs. digital signals, 194-196
arithmetic logic unit (ALU), 197
creation, 198-199
features, 197-198
multiplier, 197
pre-adder, 197
dual-port RAM, 111
\$dumpfile() function, 73
duty cycle, 47

## E

EDA Playground, 69-70, 72-74, 83, 211
edge detection, 51, 54, 179-180
electromagnetic interference (EMI), 244, 253
endmodule keyword, 22
entity keyword, 22
enumeration, 152, 171
EPWave, 74
Ethernet, 245, 247
events, state machine, 148-149

## F

fab (ASIC foundry), 7, 89
falling edge, 47
fiber optics, 253
file_open() function, 128
files, working with, 128
filter, 196
finance, 4
finite state machine (FSM). See state machine
first in, first out (FIFO), 116-117, 144-145
AE (almost empty), 118, 145
AF (almost full), 118, 145
crossing clock domains, 144
implementation, 119-122
input and output, 117-119
interface, 117
fixed-point numbers, 230-236
flip-flops, 45-46
behavior of, 48-52, 57
clock enable (EN), 46, 48-49, 61
clock input (>), 46, 48-51
creation in Verilog or VHDL, 54
data input (D), 46, 48-51
data output (Q), 46, 48-51
double-flopping, 141-142
edge detection, 51, 54
instantiation template, 189
JK and T flip-flops, 51
physical component, 63
register, 48, 53
reset, 61-63, 87, 152
synchronous vs. asynchronous resets, 62
use in RAM, 115
floating-point numbers, 230
floating (isolated) electrical ground, 245
\$fopen() function, 128
for loops, 128-131
FPGAs (field programmable gate
arrays), 1-2
applications, 4, 89
vs. ASICs, 7-9
history, 2-3
languages, 9-11
vs. microcontrollers, 5-8
picking a family and package, 126
full adder, 229
full-duplex communication, 240, 247
\$fwrite() function, 128

## G

gain, applying to a signal, 196
general purpose input/output. See GPIO
generics, 78, 109, 114, 169
Go Board, 23, 47, 102, 256
GPIO, 238-239
differential signaling, 243-245
drive strength, 242-243
operating voltage, 242
output enable (OE), 239
single-ended, 242-243
slew rate, 243, 245
guard condition, 160
GUI approach, 190-191

## H

half adder, 229
half-duplex communication, 240
hard IP, 3, 185
hard processors, 3
hardware debugging, 67
hardware description language (HDL), 9
hertz (Hz), 47
hexadecimal, 98
high impedance (aka hi-Z or tri-state), 239-240
high-speed data, 247, 251, 253
hold time $\left(t_{h}\right), 133-135$

## I

I2C (inter-integrated circuit), 240
iCE40 (FPGA family), xxi-xxiii, 14-16, 63
iCEcube2, 14-15, 20, 55-56, 190
building, 25
creating a project, 22-24
installation, 16-18
iCEstick, 256-257
ieee library, 22
if statement, 81
inference, 186
infrared (IR) cameras, 4
initial block, 73, 213
input, 239. See also GPIO
instantiation, 186-189
integrated circuit (IC), 1
Intel, 3, 16, 64
intellectual property (IP), 3
interview tips, 265-267
input/output (I/O). See GPIO
isolated (floating) electrical ground, 245

## K

Karnaugh maps, 40

## L

latches, 59-61, 124, 155
Lattice Diamond, 16, 190, 198-199

Lattice Semiconductor, 3, 14, 257
least significant bit, 98
LEDs, 15
blinking, 51-56
blinking selectively, 101-111
lighting with logic gate, 40-42
memory game, 158-183
seven-segment display, 161
showing pattern, 178-179
wiring to switch, 19
linear feedback shift register (LFSR), 99-101
applications, 100, 107
code, 106
counter, 102
pseudorandom pattern generation, 171, 177
localparam keyword, 152
logic analyzer, 87-88
logic cell, 64
logic gates, 32-36, 38
logic minimization, 40, 124
look-up table (LUT), 38-40, 54
physical component, 63
shortcomings, 45
low-pass filter (LPF), 196
low-power double data rate (LPDDR), $116,118,148,246$
LVCMOS25, 242
LVCMOS33, 242, 245
LVDS (low-voltage differential signaling), 244

## M

Manchester code, 250-252
math
precalculating results, 227
rules, 236
memory blocks, 192. See also RAM
metastability, 133-134, 141-142, 145, 191, 250
Microchip Technology, 3, 5
microcontroller, 2, 5-7
offloading math operations, 229
Microsemi. See Microchip Technology
Microsoft, 20
minimum clock period $\left(t_{c l k(\text { min })}\right), 136$

ModelSim, 69
module keyword, 21
most significant bit, 98-99, 207, 215-217
multiplexer (mux), 92-94
multiplication, 221-225, 234
multiplier, 197
multiply-accumulate (MAC)
operation, 194, 197

## N

naming convention, 22, 62, 78, 96, 121, 158, 213, 232
NAND (not and) gate, 35-36
negotiating a job offer, 267
nonrecurring engineering (NRE) cost, 7
non-synthesizable code, 127
NOR (not or) gate, 36
NOT gate, 34, 103
now keyword, 76, 128
numbers, 206, 208-211
negative, 206
representing in FPGA, 208
signed vs. unsigned, 206-208
numeric_std package, 206

## 0

one-time programmable (OTP)
FPGAs, 89
open keyword, 105, 182
operating voltage, 242
optimization, 124
OR gate, 33, 42
or keyword, 42
output enable (OE), 239
output keyword, 21-22, 239
overloading functions, 213-214

## P

parallel communication, 248-250
parallel thinking, 2, 54
parameters, $78,109,114,169$
path slack, 139
.pcf file, 20, 24
PCI, 249
period (of clock), 47-48, 55, 80, 135
phase-locked loop (PLL), 142, 185, 199-204, 252
creation, 202
inputs, 200
locked signal, 202
operation, 200
phase of a signal, 201
physical constraints file, 20, 24
pipelining, 136-140
place and route, 20, 131
constraints, $24,55,131,145,183,245$
mapping, 24
pin report, 56
timing errors, $56,131-141,145$
timing report, 56, 138
Pmod (peripheral module) connector, 16
positive edge, 54
pre-adder, 197
primitives, 144, 185-186, 190-191, 247
printed circuit board (PCB), 14
printing to console, 128
process block, 53, 57-58, 73, 213
one vs. two, 149-155
Programmable Array Logic (PAL), 39
projects
blinking an LED, 51-57
creating a memory game, 158-183
debouncing a switch, 75-84
lighting an LED with logic gates, 40-42
selectively blinking an LED, 101-111
wiring switches to LEDs, 19-28
propagation delay $\left(t_{p}\right)$, 135-136, 249
protocol, 240, 245
pulse, 103, 107
stretching, 144
push-button switch, 15, 101
debouncing, 75, 161, 169
edge detection, 180
selector, 102
wiring to LED, 19

## Q

Q notation, 231
Quartus, 16, 18
Quine-McCluskey algorithm, 40

## R

radar, 4
radiation, 4, 89
radix, 230
RAM (random-access memory), 111-116
depth, 112, 114
dual-port, 111
single-port, 111
width, 112,114
range keyword, 80
real data type, 233
reg keyword, 53, 213
register, 48
replicated logic, 128
report keyword, 128
resetting a flip-flop. See flip-flops
resize() function, 217, 219
resource utilization. See synthesis
resume tips, 260-265
rising edge, 47-49, 54, 133, 152
routing, 5

## S

sampling (analog to digital), 195
schematic, 25, 131
.sdc file, 55
selector inputs, 92-93
self-checking testbenches, 84-86
sensitivity list, 53-54, 58
sequential logic, 57-58, 61
SerDes (serializer/deserializer), 247-250, 252-253
8B/10B, 253
clock data recovery (CDR), 251, 253
DC balance, 251
encoding scheme, 250, 253
self-clocking signals, 250
speed, 247, 250
transceiver, 247
serial communication, 248-250
serial thinking, 2
set_io keyword, 24
set/reset pin, 61-63
setup time $\left(t_{\text {su }}\right), 133-136$
seven-segment display, 15, 159, 161-165
shift_left() function, 224-226
shift register, 50, 95-101, 129, 224-225
converting between serial and parallel, 97
creating delay, 96
divide by two, 225
multiply by two, 224
signals, 21-22
address, 114
analog vs. digital, 194-196
asynchronous, 141-146
clock, 47
data valid, 112, 117
declaring, 21
differential vs. single-ended, 243-245
dynamic sizing, 209
gain, applying, 196
initial condition, 86-87
input and output, 117-119
mapping to pin, 24-25
monitoring, 74-75
self-clocking, 250-252
synchronous vs. asynchronous, 248
toggling, 101-111
sign bit, 207
signed data type, 206-207, 210
signed() function, 211, 221
sign extension, 216-219
Simon (game), 158. See also testbench
simulation, 68-75
tools, 69-70
single-ended signaling, 243
single-port RAM, 111
slew rate, 243
state machine, 147-149, 152, 155, 157-160, 184
best practices, 157-158
diagram, 148-149, 158-159
events, 148-149
guard condition, 160
implementation, 149-155
initial state, $149,152,160$
memory game project, 158-183
states, 148
transitions, 148
turnstile example, 148-152
std_logic_1164 package, 22
std_logic_arith package, 206
std_logic data type, 22
std_logic_vector data type, 206, 210
subtraction, 219-221, 232-234
switches. See push-button switch
synchronous logic, 57
syntax errors, 125
synthesis, 20, 124-127 constraints, 54-55
inference, 186
logic minimization, 40
notes, 124
pruning, 105, 208
report, $42,55,60,84,124,183$
syntax errors, 125
translate directives, 127
utilization, 42, 84, 110, 183, 194, 204
errors, 125-127
warnings, 124
synthesizable code, $77,87,127-130$
system on a chip (SoC), 229
SystemVerilog, 70, 86, 89, 152

## T

$t_{c l k(\text { min })}($ minimum clock period), 136
telecommunications, 4
ternary operator, 93, 179, 241
testbench, 70-72
creating, 81-83
clock creation, 82
math operations, 211-228
running, 74-75
self-checking, 84-86
speeding up, 83
state machine, 155-158
writing, 71-73
$t_{h}$ (hold time), 133
\$time, 76, 128
time, measuring, 76-77
timing. See place and route
toggle a signal, 101-111
to_integer () function, 210-211
to_signed() function, 211
to_unsigned() function, 211
$t_{p}$ (propagation delay), 135-136, 249
transceiver, 240, 247
transition, 148
tri-state, 239
truncation, 233-234
truth tables, 32-39, 41
AND, 33
multiple gates, 37
NAND, 35
NOT, 34
OR, 34
three-input, 37
XOR, 35
$t_{\text {su }}$ (setup time), 133-136
TTL (transistor-transistor logic), 242
Turing, Alan, 33
TWI (two-wire interface), 240
two-dimensional (2D) array, 115, 175
two's complement, 207-208

## u

unit under test (UUT), 70-75, 83
universal asynchronous receivertransmitter (UART), 97-99
unsigned data type, 210
unsigned() function, 211
USB requirements, 15
utilization errors, 125-127. See also synthesis: utilization

## V

variable keyword, 213
verification, $8,88-89$
Verilog
background, 9-11
enumeration support, 152
weak typing, 10

VHDL
2008 version, 109
attributes, 211, 219
background, 9-11
data type conversions, 210-211
strong typing, 10, 178, 182, 210, 213, 217
verbosity, 22
Visual Studio Code
(VS Code), 20
Vivado, 16, 18
voltage, 46. See also GPIO

## W

wait keyword, 73, 76, 128
waveforms, 74-75, 83-84
when keyword, 61
width, 112, 114
wraparound, 208
write() function, 128

## X

Xilinx, 2-3, 16, 69
XNOR (exclusive not or) gate, 36 , 99-100, 107
XOR (exclusive or) gate, 35-36, 39, 42, 99, 250-251
xor keyword, 42

## Z

Z (high impedance), 239

