Copyright, 2021, 2022, 2023

Preface

This electronics lab manual is modeled after a much earlier version by Prof. R. Littauer of the Cornell Univ. physics department. It has been greatly revised and expanded from the original. Many chapters have been completely rewritten.

MATLAB(R) is a registered trademark of The Mathworks, Inc.

Windows is a registered trademark of Microsoft, Inc.

Mac is a registered trademark of Apple Computer, Inc.
Contents

1 INTRODUCTION (10 exp.) 1
1.1 Voltage Signals and Ground ........................................... 1
1.2 Measuring Voltages and Rise Time .................................. 2
1.3 Using the Oscilloscope ................................................. 4
   1.3.1 Vertical ............................................................... 4
   1.3.2 Horizontal ......................................................... 6
   1.3.3 Triggering ........................................................... 6
   1.3.4 Input Probes ....................................................... 8
1.4 Ideal Voltage and Current Sources .................................. 9
1.5 Resistors .................................................................. 10
1.6 Kirchhoff’s Laws ......................................................... 13
1.7 Superposition ............................................................ 14
1.8 Capacitors ............................................................... 15
1.9 Circuit Assembly ......................................................... 17
1.10 Waveshaping by R-C Circuits ...................................... 18
1.11 Low-Pass Filter ......................................................... 19
1.12 High-Pass Filter ......................................................... 23
1.13 Source Impedance (or Resistance) .................................. 25
1.14 Thevenin’s Theorem .................................................... 27
1.15 Norton’s Theorem ....................................................... 31
1.16 Source Impedance and Capacitive Loads ......................... 32
1.17 Practice Problems ...................................................... 33

2 THE OPERATIONAL AMPLIFIER (6 exp.) 35
2.1 Introduction ................................................................. 35
2.2 The Decibel .................................................................. 37
2.3 Manufacturers’ Data Books and Spec-Sheets ...................... 38
2.4 Connecting the Power Supplies ...................................... 39
2.5 Small-Signal Amplification and Input Offset Voltage .......... 40
2.6 The Overdriven Amplifier or Comparator ......................... 42
2.7 The Ideal Op-Amp ........................................................ 45
2.8 Positive Feedback and the Schmitt Trigger Circuit .............. 45
CONTENTS

2.9 Free-Running (Astable) Multivibrator or Oscillator ........................................ 48
2.10 Single-Supply Operation .................................................................................. 50
2.11 Typical Values of Some Op-amp Parameters .................................................... 51
2.12 Practice Problems ............................................................................................. 52

3 SINUSOIDAL SIGNALS (3 exp.) ............................................................................ 53
  3.1 Phasor Representation ....................................................................................... 53
  3.2 Complex Notation .............................................................................................. 54
  3.3 Complex Impedance .......................................................................................... 55
  3.4 Working with Complex Numbers ...................................................................... 55
  3.5 The Inductor .................................................................................................... 56
  3.6 The Capacitor .................................................................................................. 57
  3.7 Combinations of Elements ............................................................................... 58
  3.8 The Transfer Function and Bode Plots ............................................................. 60
  3.9 High-Pass R-C Filter ....................................................................................... 61
  3.10 Low-Pass Filter .............................................................................................. 63
  3.11 Bode Plots, Poles and Zeros .......................................................................... 64
  3.12 Bandpass Filter ............................................................................................... 67
  3.13 Computer Aided Design and Analysis ............................................................ 70
  3.14 Fourier Analysis. The Frequency Domain ....................................................... 72
  3.15 R-C Networks in the Frequency Domain ....................................................... 74
  3.16 Differentiation and Integration—the Time-Domain View ............................... 75
  3.17 A Note on Dimensions ................................................................................... 76
  3.18 Practice Problems ........................................................................................... 76

4 NEGATIVE FEEDBACK CIRCUITS (9 exp.) .......................................................... 81
  4.1 General Principles ............................................................................................ 81
  4.2 Differential and Common-Mode Signals .......................................................... 84
  4.3 The Voltage Follower ..................................................................................... 85
  4.4 Noninverting Amplifier .................................................................................... 86
  4.5 The Inverting Configuration ............................................................................ 87
  4.6 The Virtual-Ground Point: Current Control .................................................... 90
  4.7 Non-Ideal Op-Amp Properties ........................................................................ 91
  4.8 Summing with Op-Amps ................................................................................ 93
  4.9 Differential Amplifier ..................................................................................... 93
  4.10 Time Integration Using an Op-Amp ................................................................. 94
  4.11 Active Filters ................................................................................................ 96
  4.12 Integration and Bias Currents ......................................................................... 99
  4.13 Time Differentiation using Op-amps ............................................................... 101
  4.14 Nonlinear Operations .................................................................................... 103
  4.15 Stability ........................................................................................................ 103
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.13</td>
<td>Simplifying Logic with Karnaugh Maps</td>
<td>227</td>
</tr>
<tr>
<td>8.14</td>
<td>Legacy TTL and LS-TTL Logic</td>
<td>228</td>
</tr>
<tr>
<td>8.15</td>
<td>Practice Problems</td>
<td>231</td>
</tr>
<tr>
<td>9</td>
<td>SEQUENTIAL CIRCUITS (7 exp.)</td>
<td>235</td>
</tr>
<tr>
<td>9.1</td>
<td>Introduction</td>
<td>235</td>
</tr>
<tr>
<td>9.2</td>
<td>R-S Flip-Flop</td>
<td>235</td>
</tr>
<tr>
<td>9.3</td>
<td>Propagation Delay</td>
<td>238</td>
</tr>
<tr>
<td>9.4</td>
<td>D Flip-Flop</td>
<td>239</td>
</tr>
<tr>
<td>9.5</td>
<td>J-K Flip-Flops</td>
<td>242</td>
</tr>
<tr>
<td>9.6</td>
<td>Synchronous Systems and Sequential Logic</td>
<td>243</td>
</tr>
<tr>
<td>9.7</td>
<td>Registers</td>
<td>245</td>
</tr>
<tr>
<td>9.8</td>
<td>Counters</td>
<td>247</td>
</tr>
<tr>
<td>9.9</td>
<td>Initialization</td>
<td>251</td>
</tr>
<tr>
<td>9.10</td>
<td>Practice Problems</td>
<td>252</td>
</tr>
<tr>
<td>10</td>
<td>TIMING AND TRANSDUCERS (4 exp.)</td>
<td>257</td>
</tr>
<tr>
<td>10.1</td>
<td>RC Timing</td>
<td>257</td>
</tr>
<tr>
<td>10.2</td>
<td>The 555 Timer IC</td>
<td>258</td>
</tr>
<tr>
<td>10.3</td>
<td>Monostable Operation of the 555 (One Shot)</td>
<td>258</td>
</tr>
<tr>
<td>10.4</td>
<td>Astable Operation of the 555 (Oscillator)</td>
<td>260</td>
</tr>
<tr>
<td>10.5</td>
<td>74xx00 Family One-Shots</td>
<td>262</td>
</tr>
<tr>
<td>10.6</td>
<td>Clocks</td>
<td>264</td>
</tr>
<tr>
<td>10.7</td>
<td>Electronic Transducers</td>
<td>265</td>
</tr>
<tr>
<td>10.7.1</td>
<td>Distance Measurement with Ultrasonic Transducers</td>
<td>265</td>
</tr>
<tr>
<td>10.8</td>
<td>Practice Problems</td>
<td>268</td>
</tr>
<tr>
<td>11</td>
<td>LABORATORY COMPUTERS (6 exp.)</td>
<td>271</td>
</tr>
<tr>
<td>11.1</td>
<td>Computer System Description</td>
<td>272</td>
</tr>
<tr>
<td>11.1.1</td>
<td>Input and Output Connections (Buses)</td>
<td>273</td>
</tr>
<tr>
<td>11.1.2</td>
<td>Lab Computer</td>
<td>274</td>
</tr>
<tr>
<td>11.2</td>
<td>Microprocessor Evolution</td>
<td>275</td>
</tr>
<tr>
<td>11.3</td>
<td>Programming</td>
<td>277</td>
</tr>
<tr>
<td>11.4</td>
<td>Hexadecimal Numbers</td>
<td>278</td>
</tr>
<tr>
<td>11.5</td>
<td>The Arduino Microcontroller Board</td>
<td>278</td>
</tr>
<tr>
<td>11.6</td>
<td>Reading Data Into Computer From the Outside World</td>
<td>284</td>
</tr>
<tr>
<td>11.7</td>
<td>Writing Data Out of Computer</td>
<td>286</td>
</tr>
<tr>
<td>11.8</td>
<td>Digital Temperature and Humidity Sensor</td>
<td>289</td>
</tr>
<tr>
<td>11.9</td>
<td>Computer I/O Speed</td>
<td>292</td>
</tr>
<tr>
<td>11.10</td>
<td>External Synchronization (Polling)</td>
<td>292</td>
</tr>
<tr>
<td>11.11</td>
<td>Programming in Assembly Language (Intel)</td>
<td>294</td>
</tr>
<tr>
<td>11.12</td>
<td>Practice Problems</td>
<td>298</td>
</tr>
</tbody>
</table>
12 COMPUTER DATA ACQUISITION (7 exp.) 301
  12.1 Digital-to-Analog Conversion ........................................... 301
  12.2 The Ramp Generator .......................................................... 304
  12.3 Analog to Digital Conversion, the Digital Voltmeter ................. 306
  12.4 Digitization by Successive Approximations ............................. 308
  12.5 The Digital Sampling Scope ............................................... 310
  12.6 Signal Averager (Box-Car Integrator) ................................... 313
    12.6.1 Noise Generator ....................................................... 316
  12.7 Practice Problems .............................................................. 319
  
A Data Recording and Laboratory Notebooks 321

B Laboratory Equipment 325

C Manufacturers and Distributors 327

D ECAD and LTspice 329
  D.1 Introduction ........................................................................ 329
  D.2 Passive RC Circuit ............................................................... 330
    D.2.1 Time Domain ................................................................. 330
    D.2.2 Frequency Domain .......................................................... 332
  D.3 Op-Amps ............................................................................ 333
    D.3.1 Open Loop ..................................................................... 334
    D.3.2 Closed Loop .................................................................... 335
    D.3.3 Stability ........................................................................ 335
  D.4 Diodes and Transistors .......................................................... 337
  D.5 Digital Gates, Flip Flops etc. .................................................. 340
    D.5.1 Install Digital Components ............................................... 340
    D.5.2 Examples ....................................................................... 342
Appendix B

Laboratory Equipment

Each lab station is set up to accommodate two people at one time and should have the following equipment (or its equivalent):

1. Oscilloscope (min. of Tektronix TDS-1072, dual channel, 60 MHz, digital storage, 2 GS/s)
2. Function generator (sine, square and triangle waves, 0 to 2 MHz, B&K 3022)
3. Two variable power supplies (0 to ±15 volts, about 250 mAmp)
4. Solderless breadboard for circuit assembly
5. Assorted 1/4 Watt resistors (10 Ohms to 10 MegOhms)
6. Assorted capacitors (10 pfd to 220 µF)
7. Assorted wire (solid 22 gauge, BNC cables), and tools (needle nose pliers, wire cutter, wire striper, and small screwdriver for scope probe adjustments)
8. Arduino Mega microcontroller board (with digital I/O, DAC, ADC) and host computer with Arduino IDE software.
9. Other semiconductor components (transistors, diodes, integrated circuits, etc.) obtained as needed (some listed below).

- **op-amps**: 741, 3140
- **instrumentation amplifier**: AD622
- **diodes**: 1N914 (signal), 1N4007 (power), 1N4735 (zener)
- **transistors**: 2N3904 (NPN), 2N3906 (PNP), 2N7000 (n-chan. MOSFET)
- **high speed CMOS**: 74HC00 (NAND), 74HC02 (NOR), 74HC04 (inverter), 74HC08 (AND), 74HC14 (Schmit trigger inverter), 74HC32 (OR), 74HC74 (D flip flop), 74HC86 (XOR), 74HC161 (4 bit synch. counter), 74HC164 (8 bit par. out shift reg), 74HC194 (4 bit shift left/right), 74HC221 (dual one-shot), 74HC240 (octal 3-state invert. buffer) 74HC283 (4 bit adder), 74HC4066 (quad analog switch)
Misc.: 6.3VAC CT transformer, 555 (timer), 7-segment LED display, 40kHz acoustic transducer, small radio and audio speaker
Appendix C

Manufacturers and Distributors

Electronics components, from discrete components like resistors and capacitors to sophisticated integrated circuits are manufactured by a variety of different companies. However, in most cases, you do not buy the components directly form the manufactures. Instead you purchase the components from a distributor. Distributors range from large scale industrial suppliers who will only sell components in large quantities to other companies to small mail order companies that will sell small quantities of components to individuals.

In most cases you must get the specifications for the components and decide want you want before contacting the distributor. This information is available in the form of data books from the manufacturer (discussed more in chapter 2) or in many cases can be found on web sites set up by the manufacturers (a general listing of different IC‘c can be found at www.chipcenter.com). Some manufacturers web sites are listed in table C.1 (this is NOT a recommendation for or against any particular manufactures, but only a list of some sources of information). You may find the specifications for many types of electronics components on these sites.

Most distributors now have their whole catalogs on-line for easy access. Some distributors that will sell small quantities to individuals and their web sites are listed in table C.2 (again this is NOT a recommendation for or against any particular supplies, but only a list of some that are available):

There are also several companies that produce software for computer aided design of electronic circuits. Some of these companies are listed in table C.3. These programs can be useful for analyzing complicated electronic circuits. Some of these companies offer free downloads of limited-use evaluation

<table>
<thead>
<tr>
<th>Company</th>
<th>Website</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMD</td>
<td><a href="http://www.amd.com">www.amd.com</a></td>
</tr>
<tr>
<td>Analog Devices</td>
<td><a href="http://www.analog.com">www.analog.com</a></td>
</tr>
<tr>
<td>NXP</td>
<td><a href="http://www.nxp.com">www.nxp.com</a></td>
</tr>
<tr>
<td>Intel</td>
<td><a href="http://www.intel.com">www.intel.com</a></td>
</tr>
<tr>
<td>Renesas (Intersil)</td>
<td><a href="http://www.renesas.com">www.renesas.com</a></td>
</tr>
<tr>
<td>On Semiconductor</td>
<td><a href="http://www.onsemi.com">www.onsemi.com</a></td>
</tr>
<tr>
<td>Texas Instruments</td>
<td><a href="http://www.ti.com">www.ti.com</a></td>
</tr>
</tbody>
</table>

Table C.1: Some Manufactures
APPENDIX C. MANUFACTURERS AND DISTRIBUTORS

Arrow: www.arrow.com
Digi-Key: www.digikey.com
Jameco: www.jameco.com
JDR: www.jdr.com
Mouser Electronics: www.mouser.com
Newark: www.newark.com

Table C.2: Some Distributors

| Circuit Maker: | www.circuitmaker.com |
| Electronic Workbench: | www.electronicsworkbench.com |
| LTspice | www.linear.com/designtools/software |
| Spectrum Software: | www.spectrum-soft.com |
| OrCad | www.orcad.com |
| Spice | bwrc.eecs.berkeley.edu/Classes/IcBook/SPICE/ |

Table C.3: Some electronics CAD companies.

or student versions. Again this list is not a recommendation for or against any particular company but just a list of some things that are available.
Bibliography


Some books on analog electronics.


Some books on digital electronics.


Some books on computer interfacing.


Some books on semiconductor device physics and manufacturing.


Some books on grounding, and noise reduction and instrumentation.


Some books on ECAD.

Index

$V_T$, 182
$V_T^*$, 115, 155
$\alpha$, 144
$\beta$, 144
$g_m$, 155, 189
$r_b$, 156
$r_e$, 155
20 db/decade, 62
555 timer IC, 258
74xx00 one-shots, 262

AC coupling, 127, 165
active filters, 96
active low, 202
active pull-up, 222
active region, 145, 151
actuator, 265
ADC, 299, 304
addition, 214
admittance, 55
AGC, 183
aliasing, 311
all-pass filter, 109
analog signals, 35
analog transmission gate, 219
analog-to-digital converter, 304
AND, 203
angular frequency, 53
Arduino, 278
assembly language, 277
astable, 260
astable multivibrator, 48, 137
asynchronous input, 240
audible frequencies, 265

band pass filter, 108
bandpass filter, 67
base, 142
BCD, 250
beta, 144
bias, 154, 188
bias current, 134
binary, 202, 214
binary addition, 214
bit, 235, 272
bits, 214
BJT, 141
BJT circuit model, 147
Bode Plot, 60, 64
Bode, Henrik, 60
Boltzman’s constant, 115
Boolean Algebra, 208
Boolean algebra, 202, 209
Boolean identities, 209
box car integrator, 313
breadboard, 2, 17
breakdown, 116, 146
bridge rectifier, 122
bypass capacitors, 165
byte, 272, 293

CAD, 70
CAD software, 325
capacitor, 57
capacitor charging equation, 21
capacitors, 15
carry in, 215
carry out, 214
cascade, 216
CCMR, 85
center tap, 121
chopper stabilized, 91
circuit model, 147
class A amplifier, 170
class B amplifier, 170
clipping, 126
clocks, 264
closed loop gain, 82
CMOS, 205, 220
CMOS speed, 225
coaxial cable, 1
collector, 142
combinatorial logic, 201, 210, 235
common emitter amplifier, 164
common mode rejection ratio, 85
common mode signal, 84
common-emitter characteristics, 144
comparator, 42, 44, 258
compensation, 77
compiler, 277
complex impedance, 55
complex notation, 54
complex numbers, 55
computer IO bus, 273
computer system, 272
corner frequencies, 64
corner frequency, 42, 61
counters, 247
CPU, 272
cross talk, 40
cross-over distortion, 171
crystal oscillator, 264
current control, 90
current gain, 144
current source, 31, 147, 163
current to voltage converter, 90
curve tracer, 186
cutoff, 66, 145, 150, 181
D flip-flop, 239
DAC, 299
DAQ, 274
darlington pair, 166
data acquisition, 271
data acquisition port, 274
data book, 38
DC bias, 154
debounced switch, 238
decibel, 37
decoder, 217
delay circuit, 263
DeMorgan’s Theorem, 211
demultiplexer, 217
depletion mode, 179
depletion region, 114
differential, 2
differential amplifier, 93, 192
differential input voltage, 36
differential pair, 167
differential signal, 84
differential signals, 5
differentiation, 56, 75, 101
differentiator, 74
digital sampling scope, 308
digital signals, 35, 201
digital-to-analog conversion, 299
diode characteristics, 136
diode clipping circuit, 126
diode drop, 116
diode edge detector, 131
diode equation, 115
diode I-V curve, 118
diode model, 116
diode peak detector, 130
diode pulse stretcher, 129
diode ratings, 116
diode voltage drop, 116
diode wave shaping, 127
diodes, 113
distance measurement, 265
distributors, 325
duty cycle, 127, 243
ECAD, 71, 327
edge detector, 131
electrons, 114
emitter, 142
emitter bias, 161
emitter coupled pair, 167
emitter follower, 156
enhancement mode, 179
Euler’s identity, 54
exclusive-OR, 204

fall time, 3
fanout, 230
feedback, 81
filter capacitor, 124
forward bias, 115
Fourier analysis, 72
frequency, 53
frequency domain, 53, 72, 97, 101
full adder, 215
full wave bridge rectifier, 122
full wave center tap rectifier, 121
gain margin, 104
gates, 201
ground, 1

h parameters, 144
half adder, 215
half-wave rectifier, 121
Hertz, 53
hexadecimal, 278
high pass filter, 23, 61
hole, 114
hybrid parameters, 144
hysteresis, 46
I-V curve, 186
ideal current source, 10
ideal diode, 113
ideal op-amp, 45
ideal voltage source, 9
impedance, 25, 55
impedance matching, 27
inductive load, 152
inductor, 56
infinite gain approx., 82
input bias current, 91, 99, 100
input offset current, 91
input offset voltage, 40, 42, 91, 100
instability, 103
instrumentation amplifier, 94, 108, 118
integration, 57, 75, 94, 99
integrator, 74
internal compensation, 42
internal impedance, 25
internet, 245
inversion, 202
inverter, 202
inverting amplifier, 87
inverting configuration, 87
ISA bus, 273
JK flip-flop, 242
Johnson noise, 312
junction, 114
K, 182
Karnaugh Maps, 227
Kirchhoff’s Laws, 13

linear amplifier, 154
linear feedback shift register, 314
load current, 125
load line, 148
log amplifier, 132
log-log plot, 60
logic gates, 201, 202
loop gain, 82
low pass filter, 19, 63
LS-TTL, 228
LTspice, 71, 327
machine language, 277
majority carriers, 141
manufacturer’s data book, 38
manufacturers, 325
memory, 235
microphone, 265
microprocessor, 272
microprocessor evolution, 275
minority carriers, 141
modulo-16 counter, 248
monostable, 258
Moore’s law, 275
MOSFET, 179
motherboard, 272
multiplexer, 217
n-type region, 114
NAND, 204
negation, 202
negative feedback, 81
noise, 311, 314
noise generator, 314
non-ideal op-amp, 91
non-inverting amplifier, 86
non-retriggerable, 263
NOR, 204
Norton’s Theorem, 31
offset voltage, 40, 100
Ohm’s Law, 10, 55
Ohmic region, 182
one-shot, 258
op amp, 35
op-amp integrator, 94
op-amp summary, 107
open circuit, 26
open loop gain, 82
operating point, 134
Operational Amplifier, 35
operational configuration, 87
OR, 203
oscillator, 48, 137, 260
Oscilloscope, 4
overdriven op-amp, 42
p-type region, 114
parasitic capacitance, 23
passband, 66
passive filter, 96
passive filters, 96
PCI bus, 273
peak detector, 130, 138
peak voltage, 2
peak-to-peak voltage, 2
phase, 53
phase advance, 66
phase lag, 66
phase margin, 104
photodiode, 142
pickoff, 129
pickup, 1
piezoelectric crystal, 265
pinch off, 182
pn junction, 114
polar form, 56
pole-zero form, 64
poles, 64
polling, 292
positive feedback, 45, 46
potentiometers, 12
power, 169
power MOSFET, 195
power supplies, 39
precision diode, 133
primary winding, 120
probes, 8
programming, 277
Propagation Delay, 238
propagation delay, 45, 212
pulse stretcher, 129
pulse stretching, 129
push-pull amplifier, 170
python, 70
Q-point, 134, 154
quartz, 265
threshold voltage, 182

time constant, 19, 23

time domain, 53, 72

toggle, 242

totem-pole, 220

transconductance, 155, 189

transducer, 1, 272

transducers, 257, 265

transfer characteristic, 37

transfer function, 60, 64

transformer, 120

transimpedance, 90

transistor active region, 145

transistor breakdown, 146

transistor circuit model, 147

transistor cutoff, 145

transistor saturation, 145

transistors, 141, 179

transmission gate, 219

tri-state, 286

tri-state output, 226

Triode region, 182

truth table, 202

TTL, 228

TTL logic levels, 207

TTL speed, 231

ultrasonic transducer, 265

USB bus, 274

virtual ground, 87, 90

voltage, 1

voltage amplification, 37

voltage comparator, 44

voltage divider, 11, 27

voltage doubler, 123

voltage follower, 85, 105

voltage reference, 117, 138

voltage regulator, 125

wave shaping, 127, 131

XOR, 204

zener diode, 117

zero crossing distortion, 171

zeros, 64