# Contents

List of figures ........................................ page xi  
List of tables ........................................ xv  
About the authors ..................................... xvi  
To the Reader .......................................... xvii  
Acknowledgments ..................................... xviii  
Introduction ......................................... xix

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equipment familiarization: multimeter, breadboard, and oscilloscope</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.1 Multimeter</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.2 Breadboard</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1.2.1 Measuring voltage</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1.2.2 Measuring current; resistance and Ohm’s law</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1.2.3 Measuring resistance</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1.3 Oscilloscope</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>1.3.1 Probes and probe test</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>1.3.2 Display</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1.3.3 Vertical controls</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>1.3.4 Horizontal sweep</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1.3.5 Triggering</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>1.3.6 Additional features</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>RC circuits</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2.1 Review of capacitors</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2.1.1 Use of capacitors; review of AC circuits</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2.1.2 Types and values of capacitors</td>
<td>19</td>
</tr>
</tbody>
</table>
## Table of Contents

### 2. Review of current, voltage, and power
- 2.2.1 Destructive demonstration of resistor power rating
- 2.3 Potentiometer as voltage divider
  - 2.3.1 DC voltage divider
  - 2.3.2 AC voltage divider
- 2.4 RC circuit
- 2.5 RC circuit as integrator
- 2.6 Low-pass filter
- 2.7 RC circuit as differentiator
- 2.8 High-pass filter
- 2.9 Summary of high- and low-pass filters

### 3. Diodes
- 3.1 Semiconductor basics
- 3.2 Types of diodes
- 3.3 Rectification
- 3.4 Diode action – a more sophisticated view
- 3.5 Measuring the diode characteristic
- 3.6 Exploring rectification
- 3.7 Input and output impedance

### 4. Bipolar transistors
- 4.1 Bipolar-junction-transistor basics
  - 4.1.1 Basic definitions
  - 4.1.2 Simplest way to analyze transistor circuits
  - 4.1.3 Ebers–Moll transistor model
- 4.2 Experiments
  - 4.2.1 Checking transistors with a meter
  - 4.2.2 Emitter follower
  - 4.2.3 Common-emitter amplifier
  - 4.2.4 Collector as current source
  - 4.2.5 Transistor switch
- 4.3 Additional exercises
  - 4.3.1 Darlington connection
## Contents

4.3.2 Push–pull driver 62  
4.3.3 Common-base amplifier 63

---

### 5  Transistors II: FETs

5.1 Field-effect transistors 65
  
  5.1.1 FET characteristics 66  
  5.1.2 Modeling FET action 68

5.2 Exercises 69
  
  5.2.1 FET characteristics 69  
  5.2.2 FET current source 70  
  5.2.3 Source follower 71  
  5.2.4 JFET amplifier 73

---

### 6  Transistors III: differential amplifier

6.1 Differential amplifier 75
  
  6.1.1 Operating principle 76  
  6.1.2 Expected differential gain 76  
  6.1.3 Measuring the differential gain 77  
  6.1.4 Input offset voltage 78  
  6.1.5 Common-mode gain 78  

6.2 Op amps and their building blocks 79
  
  6.2.1 Current mirror 79  
  6.2.2 Differential amplifier with current-source loads 80  
  6.2.3 Improved current mirror 82  
  6.2.4 Wilson current mirror 82

---

### 7  Introduction to operational amplifiers

7.1 The 741 operational amplifier 85
  
  7.1.1 741 pinout and power connections 86  
  7.1.2 An ideal op amp 87  
  7.1.3 Gain of inverting and noninverting amplifiers 88  
  7.1.4 Op amp ‘golden rules’ 90  
  7.1.5 The nonideal op amp 90
### Contents

7.2 Experiments 91  
7.2.1 Testing open-loop gain 91  
7.2.2 Inverting amplifier 92  
7.2.3 Noninverting amplifier 93  
7.2.4 Voltage follower 94  
7.2.5 Difference amplifier 95  
7.3 Additional experiments 97  
7.3.1 Current source 97  
7.3.2 Noninverting summing amp with difference amplifier 98  

8 More op amp applications 101  
8.1 Op amp signal processing 101  
8.1.1 Differentiator 102  
8.1.2 Integrator 103  
8.1.3 Logarithmic and exponential amplifiers 105  
8.2 Experiments 106  
8.2.1 Differential and integral amplifiers 106  
8.2.2 Logarithmic and exponential amplifiers 108  
8.2.3 Op amp active rectifier 108  
8.2.4 Op amp with push–pull power driver 109  
8.3 Additional exercises 111  

9 Comparators and oscillators 113  
9.1 Experiments 113  
9.1.1 Op amp as comparator 113  
9.1.2 Unintentional feedback: oscillation 115  
9.1.3 Intentional positive feedback: Schmitt trigger 116  
9.1.4 RC relaxation oscillator 117  
9.1.5 555 timer IC 118  
9.2 Additional experiments 121  
9.2.1 Alarm! 121  
9.2.2 Sine/cosine oscillator 122  
9.2.3 Active bandpass filter 123
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Combinational logic</td>
<td>125</td>
</tr>
<tr>
<td>10.1</td>
<td>Digital logic basics</td>
<td>125</td>
</tr>
<tr>
<td>10.1.1</td>
<td>Logic levels</td>
<td>126</td>
</tr>
<tr>
<td>10.1.2</td>
<td>Logic families and history</td>
<td>127</td>
</tr>
<tr>
<td>10.1.3</td>
<td>Logic gates</td>
<td>129</td>
</tr>
<tr>
<td>10.1.4</td>
<td>Summary of Boolean algebra</td>
<td>130</td>
</tr>
<tr>
<td>10.2</td>
<td>CMOS and TTL compared</td>
<td>131</td>
</tr>
<tr>
<td>10.2.1</td>
<td>Diode logic</td>
<td>131</td>
</tr>
<tr>
<td>10.2.2</td>
<td>Transistor–transistor logic (TTL)</td>
<td>132</td>
</tr>
<tr>
<td>10.2.3</td>
<td>Complementary MOSFET logic (CMOS)</td>
<td>133</td>
</tr>
<tr>
<td>10.2.4</td>
<td>Powering TTL and TTL-compatible integrated circuits</td>
<td>136</td>
</tr>
<tr>
<td>10.3</td>
<td>Experiments</td>
<td>137</td>
</tr>
<tr>
<td>10.3.1</td>
<td>LED logic indicators and level switches</td>
<td>137</td>
</tr>
<tr>
<td>10.3.2</td>
<td>MOSFETs</td>
<td>138</td>
</tr>
<tr>
<td>10.3.3</td>
<td>CMOS NAND gate</td>
<td>140</td>
</tr>
<tr>
<td>10.3.4</td>
<td>Using NANDs to implement other logic functions</td>
<td>140</td>
</tr>
<tr>
<td>10.3.5</td>
<td>TTL quad XOR gate</td>
<td>141</td>
</tr>
<tr>
<td>10.4</td>
<td>Additional exercises</td>
<td>142</td>
</tr>
<tr>
<td>10.4.1</td>
<td>7485 4-bit magnitude comparator</td>
<td>142</td>
</tr>
<tr>
<td>11</td>
<td>Flip-flops: saving a logic state</td>
<td>143</td>
</tr>
<tr>
<td>11.1</td>
<td>General comments</td>
<td>144</td>
</tr>
<tr>
<td>11.1.1</td>
<td>Schematics</td>
<td>144</td>
</tr>
<tr>
<td>11.1.2</td>
<td>Breadboard layout</td>
<td>144</td>
</tr>
<tr>
<td>11.1.3</td>
<td>Synchronous logic</td>
<td>144</td>
</tr>
<tr>
<td>11.1.4</td>
<td>Timing diagrams</td>
<td>144</td>
</tr>
<tr>
<td>11.2</td>
<td>Flip-flop basics</td>
<td>145</td>
</tr>
<tr>
<td>11.2.1</td>
<td>Simple RS latch</td>
<td>145</td>
</tr>
<tr>
<td>11.2.2</td>
<td>D-type flip-flop</td>
<td>147</td>
</tr>
<tr>
<td>11.3</td>
<td>JK flip-flop</td>
<td>148</td>
</tr>
<tr>
<td>11.4</td>
<td>Tri-state outputs</td>
<td>149</td>
</tr>
</tbody>
</table>
### 11.5 Flip-flop applications

11.5.1 Divide-by-four from JK flip-flops 151
11.5.2 Contact bounce 152
11.5.3 Electronic coin toss 153

### 12 Monostables, counters, multiplexers, and RAM

12.1 Multivibrators 156
12.2 Counters 156
12.3 Experiments 157
12.3.1 Bi-quinary ripple counter 157
12.3.2 Monostable multivibrator 159
12.3.3 Multiplexer and finite-state machine 162
12.3.4 RAM 162

### 13 Digital ↔ analog conversion

13.1 A simple D/A converter fabricated from familiar chips 168
13.2 Tracking ADC 170
13.3 080x ADC and DAC chips 171
13.3.1 Successive-approximation ADC 171
13.4 Additional exercises 177
13.4.1 Digital recording 177
13.4.2 Successive-approximation ADC built from components 178

*Further reading*

Appendix A Equipment and supplies 185
Appendix B Common abbreviations and circuit symbols 188
Appendix C RC circuits: frequency-domain analysis 191
Appendix D Pinouts 194
Glossary of basic electrical and electronic terms 197
Index 199