Contents at a Glance

Introduction 1
1 Development of the PC 5
2 PC Components, Features, and System Design 21
3 Processor Types and Specifications 33
4 Motherboards and Buses 165
5 BIOS 281
6 Memory 355
7 The ATA/IDE Interface 409
8 Magnetic Storage 475
9 Flash and Removable Storage 547
10 Optical Storage 569
11 Video Hardware 657
12 Audio Hardware 733
13 External I/O Interfaces 757
14 Input Devices 795
15 Internet Connectivity 831
16 Local Area Networking 853
17 Power Supplies 903
18 Building or Upgrading Systems 993
19 PC Diagnostics, Testing, and Maintenance 1039
Index 1101

Scott M. Mueller
Contents

Introduction 1

1 Development of the PC 5
   Computer History: Before Personal Computers 5
   Timeline 5
   Electronic Computers 10
   Modern Computers 11
   From Tubes to Transistors 11
   Integrated Circuits 14
   History of the PC 15
   Birth of the Personal Computer 15
   The IBM Personal Computer 16
   The PC Industry 34 Years Later 17

2 PC Components, Features, and System Design 21
   What Is a PC? 21
   Who Controls PC Software? 23
   Who Controls PC Hardware? 26
   White-Box Systems 28
   System Types 29
   System Components 30

3 Processor Types and Specifications 33
   Microprocessor History 33
   The First Microprocessor 33
   PC Processor Evolution 36
   16-Bit to 64-Bit Architecture Evolution 39
   Processor Specifications 40
   Data I/O Bus 48
   Address Bus 48
   Internal Registers (Internal Data Bus) 49
   Processor Modes 49
   Processor Benchmarks 54
   Comparing Processor Performance 55
   Cache Memory 58
   Processor Features 65
   System Management Mode 65
   Superscalar Execution 66
   MMX Technology 67
   Dynamic Execution 69
   Dual Independent Bus Architecture 70
   HT Technology (Hyperthreading) 70
   Multicore Technology 72
   Hardware-Assisted Virtualization Support 73

   Processor Manufacturing 74
   PGA Chip Packaging 78
   Single Edge Contact and Single Edge Processor Packaging 80
   Processor Socket and Slot Types 81
   Socket LGA775 84
   Socket LGA1156 85
   Socket LGA1366 86
   Socket LGA1155 87
   Socket LGA2011 87
   Socket LGA1150 89
   Socket AM2/AM2+/AM3/AM3+ 89
   Socket F (1207FX) 91
   Socket FM1 92
   Socket FM2 92
   Socket FM2+ 92
   Socket AM1 (Socket FS1B) 92
   CPU Operating Voltages 93
   Math Coprocessors (Floating-Point Units) 94
   Processor Bugs and Steppings 94
   Processor Code Names 95
   P1 (086) Processors 95
   P2 (286) Processors 97
   P3 (386) Processors 98
   P4 (486) Processors 99
   P5 (586) Processors 100
   AMD-K5 102
   Intel P6 (686) Processors 103
   Pentium Pro Processors 103
   Pentium II Processors 104
   Pentium III 106
   Celeron 107
   Intel Pentium 4 and Extreme Edition Processors 108
   Intel Pentium D and Pentium Extreme Edition 110
   Intel Core Processors 112
   Intel Core 2 Family 112
   Intel (Nehalem) Core 1 Processors 116
   AMD K6 Processors 121
   AMD K7 Processors 122
   AMD Athlon 122
   AMD Duron 123
   AMD Athlon XP 124
   Athlon MP 124
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intel Chipsets</strong></td>
<td></td>
</tr>
<tr>
<td>Intel 3x and 4x Series Chipsets</td>
<td>218</td>
</tr>
<tr>
<td>Intel 5x Series Chipsets</td>
<td>220</td>
</tr>
<tr>
<td>Intel 6x Series Chipsets</td>
<td>224</td>
</tr>
<tr>
<td>Intel 7x Series Chipsets</td>
<td>225</td>
</tr>
<tr>
<td>Intel 8x Series Chipsets</td>
<td>227</td>
</tr>
<tr>
<td>Intel 9x Series Chipsets</td>
<td>229</td>
</tr>
<tr>
<td><strong>Third-Party Chipsets for Intel Processors</strong></td>
<td></td>
</tr>
<tr>
<td>SiS Chipsets</td>
<td>231</td>
</tr>
<tr>
<td>ULI Electronics Chipsets</td>
<td>231</td>
</tr>
<tr>
<td>VIA Chipsets</td>
<td>232</td>
</tr>
<tr>
<td>NVIDIA Chipsets for Intel Processors</td>
<td>232</td>
</tr>
<tr>
<td><strong>Chipsets for AMD Processors</strong></td>
<td></td>
</tr>
<tr>
<td>AMD Athlon Chipsets</td>
<td>233</td>
</tr>
<tr>
<td>AMD Athlon 64 and 64 FX Chipsets</td>
<td></td>
</tr>
<tr>
<td>AMD Sempron</td>
<td>234</td>
</tr>
<tr>
<td>AMD K10 Processors (Phenom, Phenom II, Athlon II, Athlon X2, Sempron)</td>
<td>235</td>
</tr>
<tr>
<td>AMD Bulldozer, Piledriver, Steamroller, and Excavator FX Processors</td>
<td>134</td>
</tr>
<tr>
<td><strong>System Resources</strong></td>
<td></td>
</tr>
<tr>
<td>Interrupts</td>
<td>271</td>
</tr>
<tr>
<td>DMA Channels</td>
<td>276</td>
</tr>
<tr>
<td>I/O Port Addresses</td>
<td>276</td>
</tr>
<tr>
<td><strong>Processor Troubleshooting Techniques</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Motherboards and Buses</strong></td>
<td></td>
</tr>
<tr>
<td>Motherboard Form Factors</td>
<td>165</td>
</tr>
<tr>
<td>Obsolete Form Factors</td>
<td>166</td>
</tr>
<tr>
<td>ATX and Other Modern Form Factors</td>
<td>177</td>
</tr>
<tr>
<td>Processor Sockets/Slots</td>
<td>189</td>
</tr>
<tr>
<td><strong>Chips</strong></td>
<td></td>
</tr>
<tr>
<td>Intel’s Early 386/486 Chipsets</td>
<td>201</td>
</tr>
<tr>
<td>Fifth-Generation (P5 Pentium Class)</td>
<td></td>
</tr>
<tr>
<td>Chipsets</td>
<td>202</td>
</tr>
<tr>
<td>Intel 915 Family</td>
<td>215</td>
</tr>
<tr>
<td>Intel 925X Family</td>
<td>215</td>
</tr>
<tr>
<td>Intel 945 Express Family</td>
<td>216</td>
</tr>
<tr>
<td>Intel 955X and 975X Family</td>
<td>217</td>
</tr>
<tr>
<td><strong>Third-Party Chipsets for AMD Processors</strong></td>
<td></td>
</tr>
<tr>
<td>SiS Chipsets</td>
<td>242</td>
</tr>
<tr>
<td>ULI Electronics Chipsets</td>
<td>242</td>
</tr>
<tr>
<td>VIA Chipsets</td>
<td>243</td>
</tr>
<tr>
<td>NVIDIA Chipsets for AMD Processors</td>
<td>243</td>
</tr>
<tr>
<td><strong>Super I/O Chips</strong></td>
<td></td>
</tr>
<tr>
<td>Motherboard Connectors</td>
<td>244</td>
</tr>
<tr>
<td>System Bus Types, Functions, and Features</td>
<td>255</td>
</tr>
<tr>
<td><strong>Motherboard Selection Criteria (Knowing What to Look For)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Chipset Documentation</strong></td>
<td></td>
</tr>
<tr>
<td>BIOS Basics</td>
<td>281</td>
</tr>
<tr>
<td>Motherboard ROM BIOS</td>
<td>285</td>
</tr>
<tr>
<td>ROM Hardware</td>
<td>285</td>
</tr>
<tr>
<td>ROM Shadowing</td>
<td>287</td>
</tr>
<tr>
<td>ROM Chip Types</td>
<td>287</td>
</tr>
<tr>
<td>ROM BIOS Manufacturers</td>
<td>291</td>
</tr>
<tr>
<td>BIOS Hardware/Software</td>
<td>292</td>
</tr>
<tr>
<td>Upgrading the BIOS</td>
<td>292</td>
</tr>
<tr>
<td>Where to Get Your BIOS Update</td>
<td>293</td>
</tr>
<tr>
<td>Determining Your BIOS Version</td>
<td>293</td>
</tr>
</tbody>
</table>
6 Memory 355

Memory Basics 355
ROM 357
DRAM 357
Cache Memory: SRAM 359

Memory Standards 361

Speed and Performance 362
Fast Page Mode DRAM 365
Extended Data Out RAM 366
SDRAM 367
DDR SDRAM 368
DDR2 SDRAM 370
DDR3 SDRAM 372
DDR4 SDRAM 374
RDRAM 375

Memory Modules 375
Registered Modules 382
SDR DIMM Details 383
DDR DIMM Details 384
DDR2 DIMM Details 384
DDR3 DIMM Details 384
DDR4 DIMM Details 384

Determining a Memory Module’s Size and Features 385

Memory Banks 387
Memory Module Speed 388
Parity and ECC 388
Parity Checking 390
How Parity Checking Works 391
ECC 391

RAM Upgrades 392
Upgrade Options and Strategies 393
Purchasing Memory 395
Replacing Modules with Higher-Capacity Versions 397
Installing Memory Modules 397
Troubleshooting Memory 399
Memory Defect Isolation Procedures 403
The System Logical Memory Layout 405

7 The ATA/IDE Interface 409

An Overview of the IDE Interface 409
Precursors to IDE 409
IDE Origins 410
Origins of ATA 411
ATA Standards 412
ATA-1 (ATA Interface for Disk Drives) 414
ATA-2 (ATA Interface with Extensions-2) 415
ATA-3 (ATA Interface-3) 415
ATA/ATAPI-4 (ATA with Packet Interface Extension-4) 416
ATA/ATAPI-5 (ATA with Packet Interface-5) 417
ATA/ATAPI-6 (ATA with Packet Interface-6) 417
ATA/ATAPI-7 (ATA with Packet Interface-7) 418
ATA/ATAPI-8 419

PATA 419
PATA I/O Connector 419
PATA I/O Cable 423
Longer or Rounded Cables 425
PATA Signals 425
PATA Dual-Drive Configurations 426
PATA PIO Transfer Modes 429
PATA DMA Transfer Modes 429

SATA 431
SATA Standards and Performance 431
SATA Express 432
SATA Cables and Connectors 434
eSATA 439
SATA Configuration 443
Advanced Host Controller Interface 444
Non-Volatile Memory Express 445
SATA Transfer Modes 445

ATA Features 446
ATA Commands 446
ATA Security Mode 447
Host Protected Area 448
ATAPI 449
ATA Drive Capacity Limitations 450
Prefixes for Decimal and Binary Multiples 451
BIOS Limitations 451
CHS/LBA and LBA/CHS Conversions 453
BIOS Commands Versus ATA Commands 454
CHS Limitations (the 528MB Barrier) 455
CHS Translation (Breaking the 528MB Barrier) 457
The 2.1GB and 4.2GB Barriers 459
LBA-Assist Translation 462
The 8.4GB Barrier 465
The 137GB Barrier and Beyond 466
Operating System and Other Software Limitations 468
GPT and the 2.2TB Barrier 470
PATA/SATA RAID 471
Software RAID 474

8 Magnetic Storage 475
Magnetic Storage 475
History of Magnetic Storage 475
How Magnetic Fields Are Used to Store Data 476
Read/Write Head Designs 479
Ferrite 480
Metal-In-Gap 480
Thin-Film 480
Magneto-Resistive Heads 481
Giant Magneto-Resistive Heads 482
Head Sliders 483
Data-Encoding Schemes 486
Frequency Modulation Encoding 487
Modified FM Encoding 487
Run Length Limited Encoding 488
Encoding Scheme Comparisons 489
Partial-Response, Maximum-Likelihood Decoders 490
Capacity Measurements 491
Areal Density 492
Perpendicular Magnetic Recording 495
Helium-Filled Drives 497
Shingled Magnetic Recording 497
Definition of a Hard Disk 498
Hard Drive Advancements 499
Form Factors 500
5 1/4-Inch Drive 502
3 1/2-Inch Drive 502
2 1/2-Inch Drive 502
1.8-Inch Drive 503
1-Inch Drives 503
HDD Operation 503
Data Recovery Options 505
The Ultimate HDD Analogy 506
Tracks and Sectors 507
ECC 510
Disk Formatting 515
Basic HDD Components 521
Hard Disk Platters (Disks) 522
Recording Media 522
Read/Write Heads 524
Head Actuator Mechanisms 526
Air Filters 532
Hard Disk Temperature Acclimation 534
Spindle Motors 534
Logic Boards 535
Cables and Connectors 536
Configuration Items 536
Hard Disk Features 536
Capacity 537
Performance 538
Reliability 543

9 Flash and Removable Storage 547
Alternative Storage Devices 547
Flash Memory Devices 547
CompactFlash, XQD, and CFast 549
SmartMedia 551
MultiMediaCard 551
SecureDigit 552
Sony Memory Stick 552
ATA Flash PC Card 553
Card-Picture Card 555
Solid-State Drives 553
Virtual SSD (RAMdisk) 554
Flash-Based SSDs 554
USB Flash Drives 558
Comparing Flash Memory Devices 559
SD Cards Speed Class and UHS Speed Class Markings 561
File Systems Used by Flash Memory 563
Flash Card Readers 563
Card Readers 563
ReadyBoost Support 564
Cloud-Based Storage 565
Floppy Disk Drives 566
Tape Drives 567

10 Optical Storage 569
Optical Technology 569
CD-Based Optical Technology 570
CDs: A Brief History 570
CD Construction and Technology 571
Mass-Producing CDs  571
Writable CDs  583
MultiRead Specifications  590
MultiPlay and MultiAudio  592
**Intel Processors with Integrated Graphics**  664
**AMD Desktop APUs**  667
Video Adapter Components  671
Identifying the Video and System Chipsets  673
Video RAM  674
The DAC  678
Video Display Interfaces  678
  The System Interface  678
  The Display Interface  679
TV Display Interfaces  695
**3D Graphics Accelerators**  696
  How 3D Accelerators Work  697
  APIs  700
Dual-GPU Scene Rendering  704
Monitors  707
  Display Specifications  707
  LCD and LED Technology  716
  Touchscreens  719
  Plasma Display Technology  720
  LCD and DLP Projectors  721
Using Multiple Monitors  722
  Dualview  722
  Homogeneous Adapters  723
  Heterogeneous Adapters  723
Choosing the Best Display Hardware for a Particular Task  723
Video Troubleshooting and Maintenance  724
  Troubleshooting Video Cards and Drivers  725
  Video Drivers  727
  Maintaining Monitors  728
  Testing Monitors  728
  Adjusting Monitors  729
  Bad Pixels  730
Troubleshooting Monitors  730
Repairing Monitors  731

**Audio Hardware**  733
Audio Hardware Concepts and Terms  734
  The Nature of Sound  734
  Evaluating the Quality of Your Audio Hardware  734
Sampling  735
Early PC Sound Cards  736
  Limitations of Sound Blaster Pro Compatibility  736
Microsoft Windows and Audio Support  736
  DirectX and Audio Support Hardware  737

**Contents**

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>vii</td>
<td>Contents</td>
</tr>
<tr>
<td>664</td>
<td>Intel Processors with Integrated Graphics</td>
</tr>
<tr>
<td>667</td>
<td>AMD Desktop APUs</td>
</tr>
<tr>
<td>671</td>
<td>Video Adapter Components</td>
</tr>
<tr>
<td>673</td>
<td>Identifying the Video and System Chipsets</td>
</tr>
<tr>
<td>674</td>
<td>Video RAM</td>
</tr>
<tr>
<td>678</td>
<td>The DAC</td>
</tr>
<tr>
<td>678</td>
<td>Video Display Interfaces</td>
</tr>
<tr>
<td>678</td>
<td>The System Interface</td>
</tr>
<tr>
<td>679</td>
<td>The Display Interface</td>
</tr>
<tr>
<td>695</td>
<td>TV Display Interfaces</td>
</tr>
<tr>
<td>696</td>
<td>3D Graphics Accelerators</td>
</tr>
<tr>
<td>697</td>
<td>How 3D Accelerators Work</td>
</tr>
<tr>
<td>700</td>
<td>APIs</td>
</tr>
<tr>
<td>704</td>
<td>Dual-GPU Scene Rendering</td>
</tr>
<tr>
<td>707</td>
<td>Monitors</td>
</tr>
<tr>
<td>707</td>
<td>Display Specifications</td>
</tr>
<tr>
<td>716</td>
<td>LCD and LED Technology</td>
</tr>
<tr>
<td>719</td>
<td>Touchscreens</td>
</tr>
<tr>
<td>720</td>
<td>Plasma Display Technology</td>
</tr>
<tr>
<td>721</td>
<td>LCD and DLP Projectors</td>
</tr>
<tr>
<td>722</td>
<td>Using Multiple Monitors</td>
</tr>
<tr>
<td>722</td>
<td>Dualview</td>
</tr>
<tr>
<td>723</td>
<td>Homogeneous Adapters</td>
</tr>
<tr>
<td>723</td>
<td>Heterogeneous Adapters</td>
</tr>
<tr>
<td>723</td>
<td>Choosing the Best Display Hardware for a Particular Task</td>
</tr>
<tr>
<td>724</td>
<td>Video Troubleshooting and Maintenance</td>
</tr>
<tr>
<td>725</td>
<td>Troubleshooting Video Cards and Drivers</td>
</tr>
<tr>
<td>727</td>
<td>Video Drivers</td>
</tr>
<tr>
<td>728</td>
<td>Maintaining Monitors</td>
</tr>
<tr>
<td>728</td>
<td>Testing Monitors</td>
</tr>
<tr>
<td>729</td>
<td>Adjusting Monitors</td>
</tr>
<tr>
<td>730</td>
<td>Bad Pixels</td>
</tr>
<tr>
<td>730</td>
<td>Troubleshooting Monitors</td>
</tr>
<tr>
<td>731</td>
<td>Repairing Monitors</td>
</tr>
<tr>
<td>733</td>
<td>Audio Hardware</td>
</tr>
<tr>
<td>734</td>
<td>Audio Hardware Concepts and Terms</td>
</tr>
<tr>
<td>734</td>
<td>The Nature of Sound</td>
</tr>
<tr>
<td>734</td>
<td>Evaluating the Quality of Your Audio Hardware</td>
</tr>
<tr>
<td>735</td>
<td>Sampling</td>
</tr>
<tr>
<td>736</td>
<td>Early PC Sound Cards</td>
</tr>
<tr>
<td>736</td>
<td>Limitations of Sound Blaster Pro Compatibility</td>
</tr>
<tr>
<td>736</td>
<td>Microsoft Windows and Audio Support</td>
</tr>
<tr>
<td>736</td>
<td>DirectX and Audio Support Hardware</td>
</tr>
<tr>
<td>657</td>
<td>11 Video Hardware</td>
</tr>
<tr>
<td>657</td>
<td>Display Adapters and Monitors</td>
</tr>
<tr>
<td>658</td>
<td>Video Display Adapters</td>
</tr>
<tr>
<td>658</td>
<td>Video Adapter Types</td>
</tr>
<tr>
<td>659</td>
<td>Integrated Video/Motherboard Chipsets</td>
</tr>
<tr>
<td>663</td>
<td>CPUs with Integrated Video</td>
</tr>
<tr>
<td>571</td>
<td>Mass-Producing CDs</td>
</tr>
<tr>
<td>583</td>
<td>Writable CDs</td>
</tr>
<tr>
<td>590</td>
<td>MultiRead Specifications</td>
</tr>
<tr>
<td>592</td>
<td>MultiPlay and MultiAudio</td>
</tr>
<tr>
<td>592</td>
<td>DVD</td>
</tr>
<tr>
<td>593</td>
<td>DVD History</td>
</tr>
<tr>
<td>593</td>
<td>DVD Construction and Technology</td>
</tr>
<tr>
<td>595</td>
<td>DVD Tracks and Sectors</td>
</tr>
<tr>
<td>599</td>
<td>Handling DVD Errors</td>
</tr>
<tr>
<td>601</td>
<td>DVD Capacity (Sides and Layers)</td>
</tr>
<tr>
<td>604</td>
<td>Data Encoding on the DVD Disc</td>
</tr>
<tr>
<td>604</td>
<td>Recordable DVD Standards</td>
</tr>
<tr>
<td>612</td>
<td>Multiformat Rewritable DVD Drives</td>
</tr>
<tr>
<td>613</td>
<td>BD</td>
</tr>
<tr>
<td>616</td>
<td>HD-DVD</td>
</tr>
<tr>
<td>616</td>
<td>Optical Disc Formats</td>
</tr>
<tr>
<td>616</td>
<td>CD Formats</td>
</tr>
<tr>
<td>625</td>
<td>DVD Formats and Standards</td>
</tr>
<tr>
<td>628</td>
<td>Optical Disc File Systems</td>
</tr>
<tr>
<td>634</td>
<td>Ripping/Copying Discs</td>
</tr>
<tr>
<td>635</td>
<td>“For Music Use Only” CD-R/RW Discs</td>
</tr>
<tr>
<td>635</td>
<td>CD Copy Protection</td>
</tr>
<tr>
<td>636</td>
<td>CD Digital Rights Management</td>
</tr>
<tr>
<td>636</td>
<td>DVD and Blu-ray Copy Protection</td>
</tr>
<tr>
<td>640</td>
<td>Optical Drive Performance Specifications</td>
</tr>
<tr>
<td>640</td>
<td>CD Data Transfer Rate</td>
</tr>
<tr>
<td>640</td>
<td>CD Drive Speed</td>
</tr>
<tr>
<td>641</td>
<td>DVD Drive Speed</td>
</tr>
<tr>
<td>644</td>
<td>BD Drive Speed</td>
</tr>
<tr>
<td>645</td>
<td>Access Time</td>
</tr>
<tr>
<td>646</td>
<td>Buffer/Cache</td>
</tr>
<tr>
<td>646</td>
<td>Direct Memory Access and Ultra-DMA Interface</td>
</tr>
<tr>
<td>647</td>
<td>Loading Mechanism</td>
</tr>
<tr>
<td>648</td>
<td>Other Drive Features</td>
</tr>
<tr>
<td>648</td>
<td>How to Reliably Record Optical Discs</td>
</tr>
<tr>
<td>649</td>
<td>Bootable Optical Discs—El Torito</td>
</tr>
<tr>
<td>649</td>
<td>LightScribe and LabelFlash</td>
</tr>
<tr>
<td>649</td>
<td>Troubleshooting Optical Drives</td>
</tr>
<tr>
<td>653</td>
<td>Caring for Optical Media</td>
</tr>
<tr>
<td>654</td>
<td>Updating the Firmware in an Optical Drive</td>
</tr>
</tbody>
</table>
Contents

Pointing Devices 814
Mouse Sensitivity 815
Ball-Type Mice 815
Optical Mice 815
Pointing Device Interface Types 817
Scroll Wheels 819
Mouse Troubleshooting 821
Cleaning Your Mouse 821
Alternative Pointing Devices 821

Touchscreen Technology 826
Wireless Input Devices 827
Power Management Features of Wireless Input Devices 828
Supporting Multiple Devices with a Single Transceiver 829
Troubleshooting Wireless Input Devices 829

15 Internet Connectivity 831

Internet Connectivity Trends 831
Broadband Internet Access Types 832
Cable Internet 832
Digital Subscriber Line 836
Wireless Broadband 840
Cellular Broadband 3G and 4G Services 840
Satellite Broadband 841
ISDN 844
Leased Lines 845
Comparing High-Speed Internet Access 846
Dial-Up Modems 847
Internet Connection Security 848
Having a Backup Plan in Case of Service Interruptions 849
Sharing Your Internet Connection 850
Routers for Internet Sharing 850
Modem/Router Status LEDs 851

16 Local Area Networking 853

Defining a Network 853
Types of Networks 854
Requirements for a Network 855
Client/Server Versus Peer Networks 855
Client/Server Networks 856
Peer-to-Peer Networks 857
Comparing Client/Server and Peer-to-Peer Networks 857
Network Architecture Overview 858
Wired Ethernet 860
Wireless Ethernet 862
Bluetooth 868
Contents

Power Savings 963
80 Plus 963
ENERGY STAR 965
Advanced Configuration and Power Interface 966
Power Cycling 968
Power Supply Troubleshooting 972
Overloaded Power Supplies 973
Inadequate Cooling 973
Using Digital Multimeters 974
Specialized Test Equipment 977
Power Supply Recommendations 980
Modular Cables 981
Sources for Replacement Power Supplies 982
Power-Protection Systems 982
Surge Suppressors (Protectors) 984
Network and Phone Line Surge Protectors 984
Line Conditioners 985
Backup Power 985
Real-Time Clock/Nonvolatile RAM (CMOS RAM) Batteries 988
Modern CMOS Batteries 989
Obsolete or Unique CMOS Batteries 990
CMOS Battery Troubleshooting 991

17 Power Supplies 903

The Power Supply 903
Primary Function and Operation 903
Voltage Rails 904
The Power Good Signal 906
Power Supply Form Factors 907
Modern Form Factors 910
Power Switches 925
ATX and Newer 925
PC/XT/AT and LPX Power Switches 927
Motherboard Power Connectors 928
AT/LPX Power Supply Connectors 929
ATX and ATX12V Motherboard Power Connectors 931
Backward and Forward Compatibility 944
Dell Proprietary (Nonstandard) ATX Design 946
Additional Power Connectors 946
Peripheral Power Connectors 946
Floppy (Berg) Power Connectors 947
Serial ATA Power Connectors 948
PCI Express Auxiliary Graphics Power Connectors 949
Power Supply Specifications 953
Power Supply Loading 953
Power Supply Ratings 955
Other Power Supply Specifications 956
Power Factor Correction 958
SLI-Ready and CrossFire/CrossFireX Certifications 960
Safety Certifications 960
Power-Use Calculations 961

18 Building or Upgrading Systems 993

System Components 993
Before You Start: How to Decide What to Build 995
Case and Power Supply 997
Processor 998
Motherboard 999
Memory 1001
I/O Ports 1001
Hard Disk/Solid-State Drives 1003
Removable Storage 1003
Input Devices 1004
Video Card and Display 1004
Audio Hardware 1005
Accessories 1005
Hardware and Software Resources 1006
System Assembly and Disassembly 1007
Assembly Preparation 1007
Installing the CPU and Heatsink 1011
Installing Memory Modules 1017
Mounting the New Motherboard in the Case 1018
Preparing a Modular Power Supply 1023
Connecting the Power Supply 1023
19 PC Diagnostics, Testing, and Maintenance 1039

PC Diagnostics 1039
Diagnosing Software 1039
The POST 1040
Insyde BIOS Diagnostic and Beep Codes 1053
Peripheral Diagnostics 1053
Operating System Diagnostics 1053
Commercial Diagnosing Software 1054
Free/User-Supported Diagnostics 1055
The Boot Process 1055
The Hardware Boot Process: Operating System Independent 1056
The DOS Boot Process 1061
The Windows 9x/Me Boot Process 1061
Windows 2000/XP Startup 1061
Windows Vista/7 Startup 1062
Windows 8.1/10 Startup 1063

Index 1101
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About the Authors

Scott Mueller is the president of Mueller Technical Research (MTR), an international research and corporate training firm. Since 1982, MTR has produced the industry’s most in-depth, accurate, and effective seminars, books, articles, videos, and FAQs covering PC hardware and data recovery. MTR maintains a client list that includes Fortune 500 companies, U.S. and foreign governments, major software and hardware corporations, as well as PC enthusiasts and entrepreneurs. Scott’s seminars have been presented to several thousands of PC support professionals throughout the world.

Scott personally teaches seminars nationwide covering all aspects of PC hardware (including troubleshooting, maintenance, repair, and upgrade), A+ Certification, and data recovery/forensics. He has a knack for making technical topics not only understandable, but entertaining; his classes are never boring! If you have ten or more people to train, Scott can design and present a custom seminar for your organization.

Although he has taught classes virtually nonstop since 1982, Scott is best known as the author of the longest-running, most popular, and most comprehensive PC hardware book in the world, *Upgrading and Repairing PCs*, which has become the core of an entire series of books, including *Upgrading and Repairing PCs, Upgrading and Repairing Laptops*, and *Upgrading and Repairing Windows*.

Scott’s premiere work, *Upgrading and Repairing PCs*, has sold more than two million copies, making it by far the most popular and longest-running PC hardware book on the market today. Scott has been featured in *Forbes* magazine and has written several articles for *PC World* magazine, *Maximum PC* magazine, the Scott Mueller Forum, various computer and automotive newsletters, and the *Upgrading and Repairing PCs* website.

Contact MTR directly if you have a unique book, article, or video project in mind or if you want Scott to conduct a custom PC troubleshooting, repair, maintenance, upgrade, or data-recovery seminar tailored for your organization:

Mueller Technical Research

Web: www.muellertech.com  
Email: info@muellertech.com  
Forum: www.forum.scottmueller.com

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Mark Edward Soper has helped users deal with problems with computers, digital cameras, and other personal tech devices for more than 30 years. He is the author of *PC and Gadgets Help Desk in a Book*, author of *Easy Windows 10*, as well as more than two dozen other books on Windows, digital imaging, networking, broadband Internet, CompTIA A+ Certification, and computer troubleshooting and upgrading. With this level of experience, combined with years of teaching technical classes, Mark is experienced at helping readers understand and use creative solutions to connectivity, configuration issues, data recovery, and other types of problems that can beset users of personal technology.
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As the reader of this book, you are our most important critic and commentator. We value your opinion and want to know what we're doing right, what we could do better, what areas you'd like to see us publish in, and any other words of wisdom you're willing to pass our way.

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Introduction

Welcome to *Upgrading and Repairing PCs, 22nd Edition*. Since debuting as the first book of its kind on the market in 1988, no other book on PC hardware has matched the depth and quality of the information found in this tome. This edition continues *Upgrading and Repairing PCs*’ role as not only the best-selling book of its type, but also the most comprehensive and complete PC hardware reference available. This book examines PCs in depth, outlines the differences among them, and presents options for configuring each system.

The 22nd edition of *Upgrading and Repairing PCs* provides you with the in-depth knowledge you need to work with the most recent systems and components and gives you an unexcelled resource for understanding older systems. As with previous editions, we worked to make this book keep pace with the rapid changes in the PC industry so that it continues to be the most accurate, complete, and in-depth book of its kind on the market today.

I wrote this book for all PC enthusiasts who want to know everything about their PCs: how they originated; how they’ve evolved; how to upgrade, troubleshoot, and repair them; and everything in between. This book covers the full gamut of PC-compatible systems, from the oldest 8-bit machines to the latest high-end, 64-bit multicore processors and systems. If you need to know everything about PC hardware from the original to the latest technology on the market today, this book and the accompanying information-packed disc is definitely for you.

*Upgrading and Repairing PCs* also doesn’t ignore the less glamorous PC components. Every part of your PC plays a critical role in its stability and performance. Over the course of this book, you’ll find out exactly why your motherboard’s chipset might just be the most important part of your PC and what can go wrong when you settle for a run-of-the-mill power supply that can’t get enough juice to that monster graphics card you just bought. You’ll also find in-depth coverage of technologies such as the latest Intel Haswell processors (and the Haswell Refresh!), forthcoming Intel Broadwell desktop processors and AMD Kaveri APUs (and the latest about the graphics built into Intel and AMD processors); easy-to-use software to overclock your processor; the latest Intel and AMD chipsets; the latest BIOS settings for new processors; how helium-filled hard disks and shingled magnetic recording are leading to huge new hard disk capacities; the latest eSATA and XQD flash memory cards; the newest high-performance graphics cards based on AMD and NVIDIA GPUs for the fastest 3D gaming; the latest developments in OpenGL, OpenCL, and DirectX 3D APIs; how AMD’s Mantle improves 3D gaming; USB charge while sleeping support and the new USB 3.1 interface; SATAExpress, mSATA, and M.2 interfaces; the latest satellite Internet speed boosts; choosing the right keyswitches for high-performance gaming or data entry keyboards; new HomeGrid and G.hn home network standards; and more—it’s all in here, right down to the guts-level analysis of every port on the back of or inside your system.
Book Objectives

*Upgrading and Repairing PCs* focuses on several objectives. The primary objective is to help you learn how to maintain, upgrade, and troubleshoot your PC system. To that end, *Upgrading and Repairing PCs* helps you fully understand the family of computers that has grown from the original IBM PC, including all PC-compatible systems. This book discusses all areas of system improvement, such as motherboards, processors, memory, and even case and power-supply improvements. It covers proper system and component care, specifies the most failure-prone items in various PC systems, and tells you how to locate and identify a failing component. You'll learn about powerful diagnostics hardware and software that help you determine the cause of a problem and know how to repair it.

As always, PCs are moving forward rapidly in power and capabilities. Processor performance increases with every new chip design. Upgrading and Repairing PCs helps you gain an understanding of all the processors used in PC-compatible computer systems.

This book covers the important differences between major system architectures, from the original Industry Standard Architecture (ISA) to the latest PCI Express interface standards. *Upgrading and Repairing PCs* covers each of these system architectures and their adapter boards to help you make decisions about which type of system you want to buy in the future and help you upgrade and troubleshoot such systems.

The amount of storage space available to modern PCs is increasing geometrically. *Upgrading and Repairing PCs* covers storage options ranging from larger, faster hard drives to state-of-the-art solid-state storage devices.

When you finish reading this book, you will have the knowledge to upgrade, troubleshoot, and repair almost any system and component.

The 22nd Edition Online Content

Make sure to check out Que's dedicated *Upgrading and Repairing PCs* website! Here, you’ll find a cache of helpful material to go along with the book you’re holding.

The 22nd edition of *Upgrading and Repairing PCs* includes all-new video that delivers a complete seminar on PC troubleshooting, teaching you how to identify and resolve an array of common and not-so-common PC problems.

From detailed explainers on all the tools that should be a basic part of any PC toolkit, to all the critical rules you should follow to safely operate on your PC’s internal components, in these videos Scott Mueller ensures you are armed with everything you need to know to successfully operate on your PC.

From there, Scott takes you through a complete disassembly of an All-in-One (AiO) system, showing just what you can do to keep these specialized systems running smoothly.

Finally, there is a detailed look at today’s ultra-fast solid state disk drives (SSD) and the benefits they bring to modern systems.

In addition to the all-new video you’ll find Technical Reference material, a repository of reference information that has appeared in previous editions of *Upgrading and Repairing PCs* but has been moved to the web to make room for coverage of newer technologies. You’ll also find the complete 19th edition of this book, the complete 20th edition of the book, a detailed list of acronyms, and much more available in printable PDF format. There’s more PC hardware content and knowledge here than you’re likely to find from any other single source.
I also have a private forum (www.forum.scottmueller.com) designed exclusively to support those who have purchased my recent books and DVDs. I use the forum to answer questions and otherwise help my loyal readers. If you own one of my current books or DVDs, feel free to join in and post questions. I endeavor to answer each question personally, but I also encourage knowledgeable members to respond. Anybody can view the forum without registering, but to post a question of your own you need to join. Even if you don’t join in, the forum is a tremendous resource because you can still benefit from all the reader questions I have answered over the years.

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**A Personal Note**

When asked which was his favorite Corvette, Dave McLellan, former manager of the Corvette platform at General Motors, always said, “Next year’s model.” Now with the new 22nd edition, next year’s model has just become this year’s model, until next year that is....

I believe that this book is absolutely the best book of its kind on the market, and that is due in large part to the extensive feedback I have received from both my seminar attendees and book readers. I am so grateful to everyone who has helped me with this book through each edition, as well as all the loyal readers who have been using this book, many of you since the first edition was published. I have had personal contact with many thousands of you in the seminars I have been teaching since 1982, and I enjoy your comments and even your criticisms tremendously. Using this book in a teaching environment has been a major factor in its development. Some of you might be interested to know that I originally began writing this book in early 1985; back then it was self-published and used exclusively in my PC hardware seminars before being professionally published by Que in 1988.

In one way or another, I have been writing and rewriting this book for 30 years! In that time, *Upgrading and Repairing PCs* has proven to be not only the first, but also the most comprehensive and yet approachable and easy-to-understand book of its kind. With this new edition, it is even better than ever. Your comments, suggestions, and support have helped this book to become the best PC hardware book on the market. I look forward to hearing your comments after you see this exciting new edition.

—Scott
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—Scott
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Memory Basics

This chapter discusses memory from both a physical and a logical point of view. First, you’ll examine what memory is, where it fits into the PC architecture, and how it works. Then, you’ll look at the various types of memory, speeds, and packaging of the chips and memory modules you can buy and install.

This chapter also covers the logical layout of memory, defining the various areas of memory and their uses from the system’s point of view. Because the logical layout and uses are within the “mind” of the processor, memory mapping and logical layout remain perhaps the most difficult subjects to grasp in the PC universe. This chapter contains useful information that removes the mysteries associated with memory and enables you to get the most out of your system.

Memory is the workspace for the processor. It is a temporary storage area where the programs and data being operated on by the processor must reside. Memory storage is considered temporary because the data and programs remain there only as long as the computer has electrical power or is not reset. Before the computer is shut down or reset, any data that has been changed in memory should be saved to a more permanent storage device (usually a hard disk) so it can be reloaded into memory in the future.

Main memory is normally called random access memory (RAM) because you can randomly (as opposed to sequentially) access any location. This designation is somewhat misleading and often misinterpreted. Read-only memory (ROM), for example, is also randomly accessible, yet it is usually differentiated from the system RAM because it maintains data without power and can’t normally be written to. Although a hard disk can be used as virtual random access memory, we don’t consider that RAM either.

Over the years, the definition of RAM has changed from a simple acronym to become something that means the primary memory workspace the processor uses to run programs, which usually is constructed out of a type of chip called dynamic RAM (DRAM). One of the characteristics of DRAM chips (and therefore most types of RAM in general) is that they store data dynamically, which really has two meanings. One meaning is that the information can be written to RAM repeatedly at any time. The other has to do with the fact that DRAM requires the data to be refreshed (essentially rewritten) every few milliseconds or so; faster RAM requires refreshing more often than slower RAM. A type of RAM called static RAM (SRAM) does not require the periodic refreshing.
An important characteristic of RAM in general is that data is stored only as long as the memory has electrical power.

**Note**

Both DRAM and SRAM memory maintain their contents only as long as power is present. However, a different type of memory known as flash memory can retain its contents without power, and it is most commonly used today in solid-state drives (SSDs), digital camera and player media, and USB flash drives. As far as the PC is concerned, a flash memory device emulates a disk drive (not RAM) and is accessed by a drive letter, just as with any other disk or optical drive. For more information about flash memory, see Chapter 9, "Flash and Removable Storage."

When we talk about a computer’s memory, we usually mean the RAM or physical memory in the system, which are the memory chips or modules the processor uses to store primary active programs and data. This often is confused with the term storage, which should be used when referring to things such as disk drives (although they can be used as a form of RAM called virtual memory).

RAM can refer to both the physical chips that make up the memory in the system and the logical mapping and layout of that memory. Logical mapping and layout refer to how the memory addresses are mapped to actual chips and what address locations contain which types of system information.

People new to computers often confuse main memory (RAM) with disk storage because both have capacities that are expressed in similar megabyte or gigabyte terms. The best analogy I’ve found to explain the relationship between memory and disk storage is to think of an office with a desk and a file cabinet.

In this popular analogy, the file cabinet represents the system’s hard disk, where both programs and data are stored for long-term safekeeping. The desk represents the system’s main memory, which allows the person working at the desk (acting as the processor) direct access to any files placed on it. Files represent the programs and documents you can “load” into the memory. To work on a particular file, you first must retrieve it from the cabinet and place it on the desk. If the desk is large enough, you might be able to have several files open on it at one time; likewise, if your system has more memory, you can run more or larger programs and work on more or larger documents.

Adding hard disk space to a system is similar to putting a bigger file cabinet in the office—more files can be permanently stored. And adding more memory to a system is like getting a bigger desk—you can work on more programs and data at the same time.

One difference between this analogy and the way things really work in a computer is that when a file is loaded into memory, it is a copy of the file that is actually loaded; the original still resides on the hard disk. Because of the temporary nature of memory, any files that have been changed after being loaded into memory must then be saved back to the hard disk before the system is powered off (which erases the memory). If the changed file in memory is not saved, the original copy of the file on the hard disk remains unaltered. This is like saying that any changes made to files left on the desktop are discarded when the office is closed, although the original files are still preserved in the cabinet.

Memory temporarily stores programs when they are running, along with the data being used by those programs. RAM chips are sometimes termed volatile storage because when you turn off your computer or an electrical outage occurs, whatever is stored in RAM is lost unless you saved it to your hard drive. Because of the volatile nature of RAM, many computer users make it a habit to save their work frequently—a habit I recommend. Many software applications perform periodic saves automatically to minimize the potential for data loss.

Physically, the main memory in a system is a collection of chips or modules containing chips that are usually plugged into the motherboard. These chips or modules vary in their electrical and physical designs and must be compatible with the system into which they are being installed to function...
properly. This chapter discusses the various types of chips and modules that can be installed in different systems.

To better understand physical memory in a system, you should understand which types of memory are found in a typical PC and what the role of each type is. Three main types of physical memory are used in modern PCs. (Remember, I’m talking about the type of memory chip, not the type of module that memory is stored on.)

- **ROM**—Read-only memory
- **DRAM**—Dynamic random access memory
- **SRAM**—Static RAM

The only type of memory you normally need to purchase and install in a system is DRAM. The other types are built in to the motherboard (ROM), processor (SRAM), and other components such as the video card, hard drives, and so on.

**ROM**

*Read-only memory (ROM)* is a type of memory that can permanently or semi-permanently store data. It is called read-only because it is either impossible or difficult to write to. ROM also is often referred to as nonvolatile memory because any data stored in ROM remains there, even if the power is turned off. As such, ROM is an ideal place to put the PC’s startup instructions—that is, the software that boots the system.

Note that ROM and RAM are not opposites, as some people seem to believe. Both are simply types of memory. In fact, ROM technically could be classified as a subset of the system’s RAM. In other words, a portion of the system’s random access memory address space is mapped into one or more ROM chips. This is necessary to contain the software that enables the PC to boot; otherwise, the processor would have no program in memory to execute when it was powered on.

The main ROM BIOS is contained in a ROM chip on the motherboard, but there are also adapter cards with ROMs on them. ROMs on adapter cards contain auxiliary BIOS routines and drivers needed by the particular card, especially for those cards that must be active early in the boot process, such as video cards. Cards that don’t need drivers active at boot time typically don’t have a ROM because those drivers can be loaded from the hard disk later in the boot process.

Most systems today use a type of ROM called *electrically erasable programmable ROM (EEPROM)*, which is a form of flash memory. Flash is a truly nonvolatile memory that is rewritable, enabling users to easily update the ROM or firmware in their motherboards or any other components (video cards, SCSI cards, and so on).

For more information on BIOS upgrades, see the Chapter 5 section “Upgrading the BIOS,” p. 292.

**DRAM**

Dynamic RAM (DRAM) is the type of memory chip used for most of the main memory in a modern PC. The main advantages of DRAM are that it is dense, meaning you can pack a lot of bits into a small chip, and it is inexpensive, which makes purchasing large amounts of memory affordable.

The memory cells in a DRAM chip are tiny capacitors that retain a charge to indicate a bit. The problem with DRAM is that it is dynamic—that is, its contents can be changed. With every keystroke or every mouse swipe, the contents of RAM change, and the entire contents of RAM can be wiped out by a system crash. Also, because of the design, it must be constantly refreshed; otherwise, the electrical charges in the individual memory capacitors drain and the data is lost. Refresh occurs when the system memory controller takes a tiny break and accesses all the rows of data in the memory chips. The standard refresh time is 15ms (milliseconds), which means that every 15ms, all the rows in the memory are automatically read to refresh the data.
Unfortunately, refreshing the memory takes processor time away from other tasks because each refresh cycle takes several CPU cycles to complete. In older systems, the refresh cycling could take up to 10% or more of the total CPU time, but with modern systems running in the multigigahertz range, refresh overhead is now on the order of a fraction of a percent or less of the total CPU time. Some systems allow you to alter the refresh timing parameters via the CMOS Setup. The time between refresh cycles is known as $t_{REF}$ and is expressed not in milliseconds, but in clock cycles (see Figure 6.1).

![FIGURE 6.1](image)

Current $t_{REF}$ (refresh period) for this motherboard.

**FIGURE 6.1** The refresh period dialog box and other advanced memory timings can be adjusted manually through the BIOS Setup program.

It's important to be aware that increasing the time between refresh cycles ($t_{REF}$) to speed up your system can allow some of the memory cells to begin draining prematurely, which can cause random soft memory errors to appear.

A soft error is a data error that is not caused by a defective chip. To avoid soft errors, it is usually safer to stick with the recommended or default refresh timing. Because refresh consumes less than 1% of modern system overall bandwidth, altering the refresh rate has little effect on performance. It is almost always best to use default or automatic settings for any memory timings in the BIOS Setup. Many modern systems don't allow changes to memory timings and are permanently set to automatic settings. On an automatic setting, the motherboard reads the timing parameters out of the serial presence detect (SPD) ROM found on the memory module and sets the cycling speeds to match.

DRAMs use only one transistor and capacitor pair per bit, which makes them dense, offering more memory capacity per chip than other types of memory. Currently, DRAM chips are being prepared for production with densities up to 4Gb (512MB) per chip, which at one transistor per bit requires at least 4 billion transistors. The transistor count in memory chips is much higher than in processors.
because in a memory chip the transistors and capacitors are all consistently arranged in a (normally square) grid of simple repetitive structures, unlike processors, which are much more complex circuits of different structures and elements interconnected in a highly irregular fashion.

The transistor for each DRAM bit cell reads the charge state of the adjacent capacitor. If the capacitor is charged, the cell is read to contain a 1; no charge indicates a 0. The charge in the tiny capacitors is constantly draining, which is why the memory must be refreshed constantly. Even a momentary power interruption, or anything that interferes with the refresh cycles, can cause a DRAM memory cell to lose the charge and thus the data. If this happens in a running system, it can lead to blue screens, global protection faults, corrupted files, and any number of system crashes.

DRAM is used in PC systems because it is inexpensive and the chips can be densely packed, so a lot of memory capacity can fit in a small space. Unfortunately, DRAM is also relatively slow—typically much slower than the processor. For this reason, many types of DRAM architectures have been developed to improve performance. These architectures are covered later in the chapter.

**Cache Memory: SRAM**

Another distinctly different type of memory exists that is significantly faster than most types of DRAM. SRAM stands for static RAM, which is so named because it does not need the periodic refresh rates like DRAM. Because of the way SRAMs are designed, not only are refresh rates unnecessary, but SRAM is much faster than DRAM and much more capable of keeping pace with modern processors.

SRAM memory is available in access times of 0.25ns or less, so it can keep pace with processors running 4GHz or faster. This is because of the SRAM design, which calls for a cluster of six transistors for each bit of storage. The use of transistors but no capacitors means that refresh rates are not necessary because there are no capacitors to lose their charges over time. As long as there is power, SRAM remembers what is stored. With these attributes, why don’t we use SRAM for all system memory? The answers are simple.

Compared to DRAM, SRAM is much faster but also much lower in density and much more expensive (see Table 6.1). The lower density means that SRAM chips are physically larger and store fewer bits overall. The high number of transistors and the clustered design mean that SRAM chips are both physically larger and much more expensive to produce than DRAM chips. For example, a high-density DRAM chip might store up to 4Gb (512MB) of RAM, whereas similar-sized SRAM chips can only store up to 72Mb (9MB). The high cost and physical constraints have prevented SRAM from being used as the main memory for PC systems.

**Table 6.1 Comparing DRAM and SRAM**

<table>
<thead>
<tr>
<th>Type</th>
<th>Speed</th>
<th>Density</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAM</td>
<td>Slow</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>SRAM</td>
<td>Fast</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Even though SRAM is impractical for PC use as main memory, PC designers have found a way to use SRAM to dramatically improve PC performance. Rather than spend the money for all RAM to be SRAM memory, they design in a small amount of high-speed SRAM memory, used as cache memory, which is much more cost effective. The SRAM cache runs at speeds close to or even equal to the processor and is the memory from which the processor usually directly reads from and writes to. During read operations, the data in the high-speed cache memory is resupplied from the lower-speed main memory or DRAM in advance. To convert access time in nanoseconds to MHz, use the following formula:
1 / nanoseconds × 1000 = MHz

Likewise, to convert from MHz to nanoseconds, use the following inverse formula:

\[
\frac{1}{\text{MHz}} \times 1000 = \text{nanoseconds}
\]

Today, we have memory that runs faster than 1GHz (1 nanosecond), but up until the late 1990s, DRAM was limited to about 60ns (16MHz) in speed. Up until processors were running at speeds of 16MHz, the available DRAM could fully keep pace with the processor and motherboard, meaning that there was no need for cache. However, as soon as processors crossed the 16MHz barrier, the available DRAM could no longer keep pace, and SRAM cache began to enter PC system designs. This occurred way back in 1986 and 1987 with the debut of systems with the 386 processor running at speeds of 16MHz–20MHz or faster. These were among the first PC systems to employ what’s called cache memory, a high-speed buffer made up of SRAM that directly feeds the processor. Because the cache can run at the speed of the processor, it acts as a buffer between the processor and the slower DRAM in the system. The cache controller anticipates the processor memory needs and preloads the high-speed cache memory with data. Then, as the processor calls for a memory address, the data can be retrieved from the high-speed cache rather than the much lower-speed main memory.

Cache effectiveness can be expressed by a hit ratio. This is the ratio of cache hits to total memory accesses. A hit occurs when the data the processor needs has been preloaded into the cache from the main memory, meaning the processor can read it from the cache. A cache miss is when the cache controller did not anticipate the need for a specific address and the desired data was not preloaded into the cache. In that case the processor must retrieve the data from the slower main memory, instead of the faster cache. Any time the processor reads data from main memory, the processor must wait longer because the main memory cycles at a much slower rate than the processor. As an example, if the processor with integral on-die cache is running at 3.6GHz (3,600MHz) on a 1,333MHz bus, both the processor and the integral cache would be cycling at 0.28ns, whereas the main memory would most likely be cycling almost five times more slowly at 1,333MHz (0.75ns). So, every time the 3.6GHz processor reads from main memory, it would effectively slow down to only 1,333MHz. The slowdown is accomplished by having the processor execute what are called wait states, which are cycles in which nothing is done; the processor essentially cools its heels while waiting for the slower main memory to return the desired data. Obviously, you don’t want your processors slowing down, so cache function and design become more important as system speeds increase.

To minimize the processor being forced to read data from the slow main memory, two or three stages of cache usually exist in a modern system, called Level 1 (L1), Level 2 (L2), and Level 3 (L3). The L1 cache is also called integral or internal cache because it has always been built directly into the processor as part of the processor die (the raw chip). Because of this, L1 cache always runs at the full speed of the processor core and is the fastest cache in any system. All 486 and higher processors incorporate integral L1 cache, making them significantly faster than their predecessors. L2 cache was originally called external cache because it was external to the processor chip when it first appeared. Originally, this meant it was installed on the motherboard, as was the case with all 386, 486, and first-generation Pentium systems. In those systems, the L2 cache runs at motherboard and CPU bus speed because it is installed on the motherboard and is connected to the CPU bus. You typically find the L2 cache physically adjacent to the processor socket in Pentium and earlier systems.

In the interest of improved performance, later processor designs from Intel and AMD included the L2 cache as part of the processor. In all processors since late 1999 (and some earlier models), the L2 cache is directly incorporated as part of the processor die, just like the L1 cache. In chips with on-die L2, the cache runs at the full core speed of the processor and is much more efficient. By contrast, most processors from 1999 and earlier with integrated L2 had the L2 cache in separate chips that
were external to the main processor core. The L2 cache in many of these older processors ran at only half or one-third the processor core speed. Cache speed is important, so systems having L2 cache on the motherboard were the slowest. Including L2 inside the processor made it faster, and including it directly on the processor die (rather than as chips external to the die) made it faster yet.

A third-level or L3 cache has been present in some processors since 2001. The first desktop PC processor with L3 cache was the Pentium 4 Extreme Edition, a high-end chip introduced in late 2003 with 2MB of on-die L3 cache. Although it seemed at the time that this would be a forerunner of widespread L3 cache in desktop processors, later versions of the Pentium 4 Extreme Edition (as well as its successor, the Pentium Extreme Edition) dropped the L3 cache, instead using larger L2 cache sizes to improve performance. L3 cache made a return to PC processors in 2007 with the AMD Phenom and in 2008 with the Intel Core i7, both of which have four cores on a single die. L3 is especially suited to processors with multiple cores because it provides an on-die cache that all the cores can share. Since 2009, L3 cache has become a staple in most processors with two or more cores. Figure 6.2 shows the L1/L2/L3 cache configuration as reported by CPU-Z (www.cpuid.com) for an Intel Core i5-3570K processor. For other examples, see Figures 3.2 and 3.3, p. 61-62.

FIGURE 6.2 CPU-Z screenshots showing the CPU/Cache information for an Intel Core i5-3570K processor.

The key to understanding both cache and main memory is to see where they fit in the overall system architecture. See Chapter 4 for diagrams showing recent systems with different types of cache memory.

**Memory Standards**

For memory to be as inexpensive and interchangeable as possible, industry-standard specifications for both chips and modules have been developed. The Joint Electron Device Engineering Council (JEDEC) Solid State Technology Association creates most industry-standard memory chip and module designs.

**JEDEC**

JEDEC is the semiconductor engineering standardization body of the Electronic Industries Alliance (EIA), a trade association that represents all areas of the electronics industry. JEDEC, which was created in 1960, governs the standardization of all types of semiconductor devices, integrated circuits, and modules. JEDEC has about 300 member companies, including memory, chipset, and processor manufacturers and practically any company involved in manufacturing computer equipment using industry-standard components.
The idea behind JEDEC is simple: If one company were to create a proprietary memory technology, for example, then other companies that wanted to manufacture components compliant with that memory would have to pay license fees, assuming the company that owned it was interested in licensing at all! Parts would be more proprietary in nature, causing problems with interchangeability or sourcing reasonably priced replacements. In addition, those companies licensing the technology would have no control over future changes the owner company made.

JEDEC helps to prevent that type of scenario for items such as memory by getting all the memory manufacturers to work together creating shared industry standards covering memory chips and modules. JEDEC-approved standards for memory could then be freely shared by all the member companies, and no one single company would have control over a given standard or any of the companies producing compliant components. FPM, SDRAM, DDR, DDR2, DDR3, and DDR4 SDRAM are examples of JEDEC memory standards used in PCs, whereas EDO and RDRAM are proprietary examples. You can find out more about JEDEC standards for memory and other semiconductor technology at www.jedec.org.

Because of variations on speeds (timing), voltage, and other issues, purchasing memory matching the correct industry-standard type doesn’t guarantee that it will work in a given system. Always be sure the memory you purchase works with your system or that you can get a refund or replacement if it doesn’t. Even though industry standards do exist, allowing modules from many sources to fit a given system, I normally recommend that you look for memory modules the system or memory manufacturer has approved for the system. Often you can find a list of approved modules or suppliers in the system documentation or on the system or memory module manufacturer’s website.

**Speed and Performance**

The speed and performance issues with memory are confusing to some people because of all the different ways to express the speeds of memory and processors. Memory speed was originally expressed in nanoseconds (ns), whereas the speeds of newer forms of memory are usually expressed in megahertz (MHz) and megabytes per second (MBps) instead. Processor speed was originally expressed in megahertz (MHz), whereas most current processor speeds are expressed in gigahertz (GHz).

Although all these different speed units might seem confusing, it is relatively simple to translate from one to the other.

A **nanosecond** is defined as one billionth of a second—a short piece of time indeed. To put some perspective on just how small a nanosecond really is, consider that the speed of light is 186,282 miles (299,792 kilometers) per second in a vacuum. In one billionth of a second (one nanosecond), a beam of light travels a mere 11.80 inches or 29.98 centimeters—slightly less than the length of a typical ruler!

Memory speeds have often been expressed in terms of their cycle times (or how long it takes for one cycle), whereas processor speeds have almost always been expressed in terms of their cycle speeds (number of cycles per second). Cycle time and cycle speed are actually just different ways of saying the same thing; that is, you can quote chip speeds in cycles per second, or seconds per cycle, and mean the same thing.

As an analogy, you could express the speed of a vehicle using the same relative terms. In the United States vehicle speeds are normally expressed in miles per hour. If you were driving a car at 60 miles per hour (mph), it would take 1 minute per mile (mpm). At a faster speed of 120 mph, it would take only 0.5 mpm, and at a slower 30 mph speed it would take 2.0 mpm. In other words, you could give the speeds as either mph or mpm values, and they would mean exactly the same thing.

Because it is confusing to speak in these different terms for chip speeds, I thought it would be interesting to see exactly how they compare. Table 6.2 shows the relationship between commonly used clock speeds (MHz) and the nanosecond (ns) cycle times they represent.
As you can see from Table 6.2, as clock speed increases, cycle time decreases proportionately, and vice versa.

Over the evolutionary life of the PC, main memory (what we call RAM) has had a difficult time keeping up with the processor, requiring several levels of high-speed cache memory to intercept processor requests for the slower main memory. More recently, however, systems using DDR, DDR2, DDR3, and DDR4 SDRAM have memory bus transfer rates (bandwidth) capable of equaling that of the external processor bus. When the speed of the memory bus equals the speed of the processor bus (or some even multiple thereof), main memory performance is closest to optimum for that system.
For example, using the information in Table 6.2, you can see that the 60ns DRAM memory used in the original Pentium and Pentium II PCs up until 1998 works out to be an extremely slow 16.7MHz! This slow 16.7MHz memory was installed in systems running processors up to 300MHz or faster with external processor bus speeds of up to 66MHz, resulting in a large mismatch between processor bus and main memory performance. To alleviate this performance gap, starting in 1998 the industry shifted to faster SDRAM memory, which could match the 66MHz and 100MHz processor bus speeds in use at that time. From that point forward, memory and especially memory bus performance has largely evolved in step with the processor bus, coming out with newer and faster types to match any increases in processor bus speeds.

By the year 2000, the dominant processor bus and memory speeds had increased to 100MHz and even 133MHz, called PC100 and PC133 SDRAM, respectively. Starting in early 2001, double data rate (DDR) SDRAM memory of 200MHz and 266MHz became popular. In 2002, DDR memory increased to 333MHz, and in 2003, the speeds increased further to 400MHz. In 2004, we saw the introduction of DDR2, first at 400MHz and then at 533MHz. DDR2 memory continued to match processor bus speed increases in PCs from 2005 to 2006, rising to 667MHz and 800MHz during that time. By 2007, DDR2 memory was available at speeds of up to 1066MHz. By late 2007, DDR3 came on the market at speeds of 1066MHz, with 1333MHz and 1600MHz appearing in 2008. In 2009, DDR3 memory became the most popular memory type in new systems, and faster speed grades of 1866MHz and 2133MHz were added. DDR4 was released in 2013, with a speed of 1600MHz and expected future speeds of up to 3200MHz. DDR4-based systems began to reach the market in late summer 2014. Table 6.3 lists the primary types and performance levels of PC memory.

### Table 6.3 PC Memory Types and Performance Levels

<table>
<thead>
<tr>
<th>Memory Type</th>
<th>Years Popular</th>
<th>Desktop Module Type</th>
<th>Laptop Module Type</th>
<th>Voltage</th>
<th>Max. Clock Speed</th>
<th>Max. Throughput Single-Channel</th>
<th>Max. Throughput Dual-Channel</th>
<th>Max. Throughput Triple-Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Page Mode (FPM) DRAM</td>
<td>1987–1995</td>
<td>30/72-pin SIMM</td>
<td>72/144-pin SODIMM</td>
<td>5V</td>
<td>22MHz</td>
<td>177MBps</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Extended Data Out (EDO) DRAM</td>
<td>1995–1998</td>
<td>72-pin SIMM</td>
<td>72/144-pin SODIMM</td>
<td>5V</td>
<td>33MHz</td>
<td>266MBps</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Single Data Rate (SDR) SDRAM</td>
<td>1998–2002</td>
<td>168-pin DIMM</td>
<td>144-pin SODIMM</td>
<td>3.3V</td>
<td>133MHz</td>
<td>1,066MBps</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Double Data Rate (DDR) SDRAM</td>
<td>2002–2005</td>
<td>184-pin DIMM</td>
<td>200-pin SODIMM</td>
<td>2.5V</td>
<td>400MTps</td>
<td>3,200MBps</td>
<td>6,400MBps</td>
<td>N/A</td>
</tr>
<tr>
<td>DDR2 SDRAM</td>
<td>2005–2009</td>
<td>240-pin DDR2 DIMM</td>
<td>200-pin SODIMM</td>
<td>1.8V</td>
<td>1,066MTps</td>
<td>8,533MBps</td>
<td>17,066MBps</td>
<td>N/A</td>
</tr>
<tr>
<td>DDR3 SDRAM</td>
<td>2009–2015</td>
<td>240-pin DDR3 DIMM</td>
<td>204-pin SODIMM</td>
<td>1.5V</td>
<td>2,133MTps</td>
<td>17,066MBps</td>
<td>34,133MBps</td>
<td>51,200MBps</td>
</tr>
<tr>
<td>DDR4 SDRAM</td>
<td>2015+</td>
<td>284-pin DDR4 DIMM</td>
<td>256-pin SODIMM</td>
<td>1.2V</td>
<td>4,266MTps</td>
<td>34,133MBps</td>
<td>68,266MBps</td>
<td>102,400MBps</td>
</tr>
</tbody>
</table>

MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
DIMM = Dual inline memory module  
SODIMM = Small outline DIMM  
SIMM = Single inline memory module
Another specification to consider that is related to speed is the CAS (column address strobe) latency, which is often abbreviated as CL. This is also sometimes called read latency, and it’s the number of clock cycles occurring between the registration of the CAS signal and the resultant output data, with lower numbers of cycles indicating faster (better) performance. If possible, choose modules with a lower CL figure because the motherboard chipset reads that specification out of the SPD (serial presence detect) ROM on the module and takes advantage of the lower latency through improved memory controller timings. Figure 6.3 shows the memory timing and SPD information as reported by CPU-Z (www.cpuid.com) for a system with DDR3-1600 SDRAM.

The following sections look at these memory types in more detail.

**Fast Page Mode DRAM**

Standard DRAM is accessed through a technique called paging. Normal memory access requires that a row and column address be selected, which takes time. Paging enables faster access to all the data within a given row of memory by keeping the row address the same and changing only the column. Memory that uses this technique is called Page Mode or Fast Page Mode memory. Other variations on Page Mode were called Static Column or Nibble Mode memory.

Paged memory is a simple scheme for improving memory performance that divides memory into pages ranging from 512 bytes to a few kilobytes long. The paging circuitry then enables memory locations in a page to be accessed with fewer wait states. If the desired memory location is outside the current page, one or more wait states are added while the system selects the new page.

To improve further on memory access speeds, systems have evolved to enable faster access to DRAM. One important change was the implementation of burst mode access in the 486 and later processors. Burst mode cycling takes advantage of the consecutive nature of most memory accesses. After setting up the row and column addresses for a given access, using burst mode, you can then access the next three adjacent addresses with no additional latency or wait states. A burst access usually is limited to four total accesses. To describe this, we often refer to the timing in the number of cycles for each access. A typical burst mode access of standard DRAM is expressed as x-y-y-y; x is the time for the first access (latency plus cycle time), and y represents the number of cycles required for each consecutive access.
Standard 60ns-rated DRAM normally runs 5-3-3-3 burst mode timing. This means the first access takes a total of five cycles (on a 66MHz system bus, this is about 75ns total, or 5 × 15ns cycles), and the consecutive cycles take three cycles each (3 × 15ns = 45ns). As you can see, the actual system timing is somewhat less than the memory is technically rated for. Without the bursting technique, memory access would be 5-5-5-5 because the full latency is necessary for each memory transfer. The 45ns cycle time during burst transfers equals about a 22.2MHz effective clock rate; on a system with a 64-bit (8-byte) wide memory bus, this would result in a maximum throughput of 177MBps (22.2MHz × 8 bytes = 177MBps).

DRAM memory that supports paging and this bursting technique is called Fast Page Mode (FPM) memory. This term refers to the ability to access data on the same memory page faster than data on other memory pages.

Most 386, 486, and Pentium systems from 1987 through 1995 used FPM memory, which came in either 30-pin or 72-pin SIMM form.

Another technique for speeding up FPM memory is called interleaving. In this design, two separate banks of memory are used together, alternating access from one to the other as even and odd bytes. While one is being accessed, the other is being precharged, when the row and column addresses are being selected. Then, by the time the first bank in the pair is finished returning data, the second bank in the pair is finished with the latency part of the cycle and is now ready to return data. While the second bank is returning data, the first bank is being precharged, selecting the row and column address of the next access. This overlapping of accesses in two banks reduces the effect of the latency or precharge cycles and allows for faster overall data retrieval. The only problem is that to use interleaving, you must install identical pairs of banks together, doubling the number of modules required.

**Extended Data Out RAM**

In 1995, a newer type of DRAM called extended data out (EDO) RAM became available for Pentium systems. EDO, a modified form of FPM memory, is sometimes referred to as Hyper Page mode. EDO was invented and patented by Micron Technology, although Micron licensed production to many other memory manufacturers.

EDO memory consists of specially manufactured chips that allow a timing overlap between successive accesses. The name extended data out refers specifically to the fact that, unlike FPM, the data output drivers on the chip are not turned off when the memory controller removes the column address to begin the next cycle. This enables the next cycle to overlap the previous one, saving approximately 10ns per cycle.

The effect of EDO is that cycle times are improved by enabling the memory controller to begin a new column address instruction while it is reading data at the current address. This is almost identical to what was achieved in older systems by interleaving banks of memory, but unlike interleaving, with EDO you didn’t need to install two identical banks of memory in the system at a time.

EDO RAM allows for burst mode cycling of 5-2-2-2, compared to the 5-3-3-3 of standard fast page mode memory. To do four memory transfers, then, EDO would require 11 total system cycles, compared to 14 total cycles for FPM. This is a 22% improvement in overall cycling time. The resulting two-cycle (30ns) cycle time during burst transfers equals a 33.3MHz effective clock rate, compared to 45ns/22MHz for FPM. On a system with a 64-bit (8-byte) wide memory bus, this would result in a maximum throughput of 266MBps (33.3MHz × 8 bytes = 266MBps). Due to the processor cache, EDO typically increased overall system benchmark speed by only 5% or less. Even though the overall system improvement was small, the important thing about EDO was that it used the same basic DRAM chip design as FPM, meaning that there was practically no additional cost over FPM. In fact, in its heyday EDO cost less than FPM yet offered higher performance.
EDO RAM generally came in 72-pin SIMM form. Figure 6.4 (later in this chapter) shows the physical characteristics of these SIMMs.

To actually use EDO memory, your motherboard chipset had to support it. Most motherboard chipsets introduced on the market from 1995 (Intel 430FX) through 1997 (Intel 430TX) offered support for EDO, making EDO the most popular form of memory in PCs from 1995 through 1998. Because EDO memory chips cost the same to manufacture as standard chips, combined with Intel’s support of EDO in motherboard chipsets, the PC market jumped on the EDO bandwagon full force.

SDRAM

SDRAM is short for synchronous DRAM, a JEDEC standard for a type of DRAM that runs in synchronization with the memory bus. SDRAM delivers information in very high-speed bursts using a high-speed clocked interface. SDRAM removes most of the latency involved in asynchronous DRAM because the signals are already in synchronization with the motherboard clock.

As with any newly introduced type of memory on the market, motherboard chipset support is required before it can be usable in systems. Starting in 1996 with the 430VX and 430TX, most of Intel’s chipsets began to support industry-standard SDRAM, and in 1998 the introduction of the 440BX chipset caused SDRAM to eclipse EDO as the most popular type on the market.

SDRAM performance is dramatically improved over that of FPM or EDO RAM. However, because SDRAM is still a type of DRAM, the initial latency is the same, but burst mode cycle times are much faster than with FPM or EDO. SDRAM timing for a burst access would be 5-1-1-1, meaning that four memory reads would complete in only eight system bus cycles, compared to 11 cycles for EDO and 14 cycles for FPM. This makes SDRAM almost 20% faster than EDO.

Besides being capable of working in fewer cycles, SDRAM is capable of supporting up to 133MHz (7.5ns) system bus cycling. Most PC systems sold from 1998 through 2002 included SDRAM memory.

SDRAM is sold in DIMM form and is normally rated by clock speed (MHz) rather than cycling time (ns), which was confusing during the initial change from FPM and EDO DRAM. Figure 6.5 (later in this chapter) shows the physical characteristics of DIMMs.

To meet the stringent timing demands of its chipsets, Intel created specifications for SDRAM called PC66 and PC100. For example, you would think 10ns would be considered the proper rating for 100MHz operation, but the PC100 specification promoted by Intel called for faster 8ns memory to ensure all timing parameters could be met with sufficient margin for error.

In May 1999, JEDEC created a specification called PC133. It achieved this 33MHz speed increase by taking the PC100 specification and tightening up the timing and capacitance parameters. The faster PC133 quickly caught on for any systems running a 133MHz processor bus. The original chips
used in PC133 modules were rated for exactly 7.5ns or 133MHz; later chips were rated at 7.0ns, which is technically 143MHz. These faster chips were still used on PC133 modules, but they allowed for improvements in column address strobe latency (abbreviated as CAS or CL), which somewhat improves overall memory cycling time.

SDRAM normally came in 168-pin DIMMs, running at several speeds. Table 6.4 shows the standard single data rate SDRAM module speeds and resulting throughputs.

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Chip Type</th>
<th>Clock Speed</th>
<th>Cycles per Clock</th>
<th>Bus Speed</th>
<th>Bus Width</th>
<th>Transfer Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC66</td>
<td>15ns</td>
<td>66MHz</td>
<td>1</td>
<td>66MTps</td>
<td>8 bytes</td>
<td>533MBps</td>
</tr>
<tr>
<td></td>
<td>10ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC100</td>
<td>8ns</td>
<td>100MHz</td>
<td>1</td>
<td>100MTps</td>
<td>8 bytes</td>
<td>800MBps</td>
</tr>
<tr>
<td>PC133</td>
<td>7.5ns</td>
<td>133MHz</td>
<td>1</td>
<td>133MTps</td>
<td>8 bytes</td>
<td>1,066MBps</td>
</tr>
<tr>
<td></td>
<td>7ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)

◊◊ See “Memory Modules,” p. 375.

Some module manufacturers sold modules they claimed were “PC150” or “PC166,” even though those speeds did not exist as official JEDEC or Intel standards, and no chipsets or processors officially supported those speeds. These modules actually used hand-picked 133MHz-rated chips that could run overclocked at 150MHz or 166MHz speeds. In essence, PC150 or PC166 memory was PC133 memory that was tested to run at overclocked speeds not supported by the original chip manufacturer. This overclockable memory was sold at a premium to enthusiasts who wanted to overclock their motherboard chipsets, thereby increasing the speed of the processor and memory bus.

Caution

In general, PC133 memory is considered to be backward compatible with PC100 memory. However, some chipsets or motherboards had more specific requirements for specific types of 100MHz or 133MHz chips and module designs. If you need to upgrade an older system that requires PC100 memory, you should not purchase PC133 memory unless the memory is specifically identified by the memory vendor as being compatible with the system. You can use the online memory-configuration tools provided by most major memory vendors to ensure that you get the right memory for your system.

Typically, you find SDRAM modules rated CL 2 or CL 3.

DDR SDRAM

DDR SDRAM memory is a JEDEC standard that is an evolutionary upgrade in which data transfers twice as quickly as standard SDRAM. Instead of doubling the actual clock rate, DDR memory achieves the doubling in performance by transferring twice per transfer cycle: once at the leading (falling) edge and once at the trailing (rising) edge of the cycle (see Figure 6.4). This effectively doubles the transfer rate, even though the same overall clock and timing signals are used. To eliminate confusion with DDR, regular SDRAM is often called single data rate (SDR).
FIGURE 6.4 SDR versus DDR cycling.

DDR SDRAM first came to market in the year 2000 and was initially used on high-end graphics cards because there were no motherboard chipsets to support it at the time. DDR finally became popular in 2002 with the advent of mainstream supporting motherboards and chipsets. From 2002 through 2005, DDR was the most popular type of memory in mainstream PCs. DDR SDRAM uses a DIMM module design with 184 pins. Figure 6.6 (later in this chapter) shows the 184-pin DDR DIMM.

DDR DIMMs come in a variety of speed or throughput ratings and normally run on 2.5 volts. Table 6.5 compares the types of industry-standard DDR SDRAM modules. As you can see, the raw chips are designated by their speed in megatransfers per second, whereas the modules are designated by their approximate throughput in megabytes per second.

Table 6.5 JEDEC Standard DDR Module (184-Pin DIMM) Speeds and Transfer Rates

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Chip Type</th>
<th>Base Clock Speed</th>
<th>Cycle Time</th>
<th>Cycles per Clock</th>
<th>Bus Speed</th>
<th>Bus Width</th>
<th>Module Transfer Rate</th>
<th>Dual-Channel Transfer Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1600</td>
<td>DDR200</td>
<td>100MHz</td>
<td>10.0ns</td>
<td>2</td>
<td>200MTps</td>
<td>8 bytes</td>
<td>1,600MBps</td>
<td>3,200MBps</td>
</tr>
<tr>
<td>PC2100</td>
<td>DDR266</td>
<td>133MHz</td>
<td>7.5ns</td>
<td>2</td>
<td>266MTps</td>
<td>8 bytes</td>
<td>2,133MBps</td>
<td>4,266MBps</td>
</tr>
<tr>
<td>PC2700</td>
<td>DDR333</td>
<td>166MHz</td>
<td>6.0ns</td>
<td>2</td>
<td>333MTps</td>
<td>8 bytes</td>
<td>2,667MBps</td>
<td>5,333MBps</td>
</tr>
<tr>
<td>PC3200</td>
<td>DDR400</td>
<td>200MHz</td>
<td>5.0ns</td>
<td>2</td>
<td>400MTps</td>
<td>8 bytes</td>
<td>3,200MBps</td>
<td>6,400MBps</td>
</tr>
</tbody>
</table>

DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)

The major memory chip and module manufacturers normally produce parts that conform to the official JEDEC standard speed ratings. However, to support overclocking, several memory module manufacturers purchase unmarked and untested chips from the memory chip manufacturers and then independently test and sort them by how fast they run. These are then packaged into modules with
unofficial designations and performance figures that exceed the standard ratings. Table 6.6 shows the popular unofficial speed ratings I’ve seen on the market. Note that because the speeds of these modules are beyond the standard default motherboard and chipset speeds, you won’t see an advantage to using them unless you are overclocking your system to match.

Table 6.6 Overclocked (Non-JEDEC) DDR Module (184-Pin DIMM) Speeds and Transfer Rates

<table>
<thead>
<tr>
<th>Module Standard</th>
<th>Chip Type</th>
<th>Clock Speed (MHz)</th>
<th>Cycles per Clock</th>
<th>Bus Speed (MTps)</th>
<th>Bus Width (Bytes)</th>
<th>Transfer Rate (MBps)</th>
<th>Dual-Channel Transfer Rate (MBps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC3500</td>
<td>DDR433</td>
<td>216</td>
<td>2</td>
<td>433</td>
<td>8</td>
<td>3,466</td>
<td>6,933</td>
</tr>
<tr>
<td>PC3700</td>
<td>DDR466</td>
<td>233</td>
<td>2</td>
<td>466</td>
<td>8</td>
<td>3,733</td>
<td>7,466</td>
</tr>
<tr>
<td>PC4000</td>
<td>DDR500</td>
<td>250</td>
<td>2</td>
<td>500</td>
<td>8</td>
<td>4,000</td>
<td>8,000</td>
</tr>
<tr>
<td>PC4200</td>
<td>DDR533</td>
<td>266</td>
<td>2</td>
<td>533</td>
<td>8</td>
<td>4,266</td>
<td>8,533</td>
</tr>
<tr>
<td>PC4400</td>
<td>DDR550</td>
<td>275</td>
<td>2</td>
<td>550</td>
<td>8</td>
<td>4,400</td>
<td>8,800</td>
</tr>
<tr>
<td>PC4800</td>
<td>DDR600</td>
<td>300</td>
<td>2</td>
<td>600</td>
<td>8</td>
<td>4,800</td>
<td>9,600</td>
</tr>
</tbody>
</table>

DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)

Most chipsets that support DDR also support dual-channel operation—a technique in which two matching DIMMs are installed to function as a single bank, with double the bandwidth of a single module. For example, if a chipset supports standard PC3200 modules, the bandwidth for a single module would be 3,200MBps. However, in dual-channel mode, the total bandwidth would double to 6,400MBps. Dual-channel operation optimizes PC design by ensuring that the CPU bus and memory bus both run at the same speeds (meaning throughput, not MHz) so that data can move synchronously between the buses without delays.

The cycle time in nanoseconds (billionths of a second) matches the base clock speed, but DDR modules transfer twice per cycle, so the bus speed frequency is always equal to double the clock frequency. The throughput or bandwidth is simply the bus frequency times the width, which gives the rate at which data can be read from or written to the module.

Typically, you can find DDR modules rated CL 2, CL 2.5, or CL 3.

With DDR, it is generally okay to install a module that is faster than the system requires, but you should not install a slower module than the motherboard requires. For example, you can usually install PC2700 memory even if the system requires only PC2100 or even PC1600, but if the system requires PC2700, you should not install the slower PC2100 or PC1600 modules.

**DDR2 SDRAM**

DDR2 is a faster version of DDR memory. It achieves higher throughput by using differential pairs of signal wires to allow faster signaling without noise and interference problems. DDR2 is still double data rate just as with DDR, but the modified signaling method enables you to achieve higher clock speeds with more immunity to noise and crosstalk between the signals. The additional signals required
for differential pairs add to the pin count—DDR2 DIMMs have 240 pins, which is more than the 184 pins of DDR. The original DDR specification officially topped out at 400MHz (although faster unofficial overclocked modules were produced), whereas DDR2 starts at 400MHz and goes up to an official maximum of 1,066MHz.

JEDEC began working on the DDR2 specification in April 1998 and published the standard in September 2003. DDR2 chip and module production actually began in mid-2003 (mainly samples and prototypes), and the first chipsets, motherboards, and systems supporting DDR2 appeared for Intel processor-based systems in mid-2004. At that time, variations of DDR2 such as G-DDR2 (Graphics DDR2) began appearing in graphics cards as well. Mainstream motherboard chipset support for DDR2 on Intel processor-based systems appeared in 2005. Notable for its lack of DDR2 support through 2005 was AMD, whose Athlon 64 and Opteron processor families included integrated DDR memory controllers. AMD processor-based systems first supported DDR2 in mid-2006, with the release of socket AM2 motherboards and processors to match. (AMD’s Socket F, otherwise known as 1207 FX, also supports DDR2 memory.)

Note that AMD was almost two years behind Intel in the transition from DDR to DDR2. This is because AMD included the memory controller in its Athlon 64 and all subsequent processors, rather than incorporating the memory controller in the chipset North Bridge, as with the more traditional Intel designs. Although there are advantages to integrating the memory controller in the CPU, one disadvantage is the inability to quickly adopt new memory architectures because doing so requires that both the processor and processor socket be redesigned. However, with the release of the Core i-series processors in 2008, Intel also moved the memory controller from the chipset into the processor, thus putting Intel and AMD in the same situation in terms of memory architecture.

In addition to providing greater speeds and bandwidth, DDR2 has other advantages. It uses lower voltage than conventional DDR (1.8V versus 2.5V), so power consumption and heat generation are reduced. Because of the greater number of pins required on DDR2 chips, the chips typically use fine-pitch ball grid array (FBGA) packaging rather than the thin small outline package (TSOP) chip packaging used by most DDR and conventional SDRAM chips. FPGA chips connect to the substrate (meaning the memory module in most cases) via tightly spaced solder balls on the base of the chip.

Table 6.7 shows the various official JEDEC-approved DDR2 module types and bandwidth specifications.

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Chip Type</th>
<th>Base Clock Speed</th>
<th>Cycle Time</th>
<th>Cycles per Clock</th>
<th>Bus Speed</th>
<th>Bus Width</th>
<th>Module Transfer Rate</th>
<th>Dual-Channel Transfer Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC2-3200</td>
<td>DDR2-400</td>
<td>200MHz</td>
<td>5.00ns</td>
<td>2</td>
<td>400MTps</td>
<td>8 bytes</td>
<td>3,200MBps</td>
<td>6,400MBps</td>
</tr>
<tr>
<td>PC2-4200</td>
<td>DDR2-533</td>
<td>266MHz</td>
<td>3.75ns</td>
<td>2</td>
<td>533MTps</td>
<td>8 bytes</td>
<td>4,266MBps</td>
<td>8,533MBps</td>
</tr>
<tr>
<td>PC2-5300</td>
<td>DDR2-667</td>
<td>333MHz</td>
<td>3.00ns</td>
<td>2</td>
<td>667MTps</td>
<td>8 bytes</td>
<td>5,333MBps</td>
<td>10,667MBps</td>
</tr>
<tr>
<td>PC2-6400</td>
<td>DDR2-800</td>
<td>400MHz</td>
<td>2.50ns</td>
<td>2</td>
<td>800MTps</td>
<td>8 bytes</td>
<td>6,400MBps</td>
<td>12,800MBps</td>
</tr>
<tr>
<td>PC2-8500</td>
<td>DDR2-1066</td>
<td>533MHz</td>
<td>1.88ns</td>
<td>2</td>
<td>1,066MTps</td>
<td>8 bytes</td>
<td>8,533MBps</td>
<td>17,066MBps</td>
</tr>
</tbody>
</table>

DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)
The fastest official JEDEC-approved standard is DDR2-1066, which is composed of chips that run at an effective speed of 1,066MHz (really megatransfers per second), resulting in modules designated PC2-8500 having a bandwidth of 8,533MBps. However, just as with DDR, many of the module manufacturers produce even faster modules designed for overclocked systems. These are sold as modules with unofficial designations and performance figures that exceed the standard ratings. Table 6.8 shows the popular unofficial speed ratings I’ve seen on the market. Note that because the speeds of these modules are beyond the standard default motherboard and chipset speeds, you won’t see an advantage to using these unless you are overclocking your system to match.

Table 6.8 Overclocked (Non-JEDEC) DDR2 Module (240-Pin DIMM) Speeds and Transfer Rates

<table>
<thead>
<tr>
<th>Module Standard</th>
<th>Chip Type</th>
<th>Clock Speed (MHz)</th>
<th>Cycles per Clock</th>
<th>Bus Speed (MTps)</th>
<th>Bus Width (Bytes)</th>
<th>Transfer Rate (MBps)</th>
<th>Dual Channel-Transfer Rate (MBps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC2-6000</td>
<td>DDR2-750</td>
<td>375</td>
<td>2</td>
<td>750</td>
<td>8</td>
<td>6,000</td>
<td>12,000</td>
</tr>
<tr>
<td>PC2-7200</td>
<td>DDR2-900</td>
<td>450</td>
<td>2</td>
<td>900</td>
<td>8</td>
<td>7,200</td>
<td>14,400</td>
</tr>
<tr>
<td>PC2-8000</td>
<td>DDR2-1000</td>
<td>500</td>
<td>2</td>
<td>1000</td>
<td>8</td>
<td>8,000</td>
<td>16,000</td>
</tr>
<tr>
<td>PC2-8800</td>
<td>DDR2-1100</td>
<td>550</td>
<td>2</td>
<td>1100</td>
<td>8</td>
<td>8,800</td>
<td>17,600</td>
</tr>
<tr>
<td>PC2-8888</td>
<td>DDR2-1111</td>
<td>556</td>
<td>2</td>
<td>1111</td>
<td>8</td>
<td>8,888</td>
<td>17,777</td>
</tr>
<tr>
<td>PC2-9136</td>
<td>DDR2-1142</td>
<td>571</td>
<td>2</td>
<td>1142</td>
<td>8</td>
<td>9,136</td>
<td>18,272</td>
</tr>
<tr>
<td>PC2-9200</td>
<td>DDR2-1150</td>
<td>575</td>
<td>2</td>
<td>1150</td>
<td>8</td>
<td>9,200</td>
<td>18,400</td>
</tr>
<tr>
<td>PC2-9600</td>
<td>DDR2-1200</td>
<td>600</td>
<td>2</td>
<td>1200</td>
<td>8</td>
<td>9,600</td>
<td>19,200</td>
</tr>
<tr>
<td>PC2-10000</td>
<td>DDR2-1250</td>
<td>625</td>
<td>2</td>
<td>1250</td>
<td>8</td>
<td>10,000</td>
<td>20,000</td>
</tr>
</tbody>
</table>

DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)

Typically, you can find DDR2 modules rated between CL 3 and CL 6.

**DDR3 SDRAM**

DDR3 enables higher levels of performance along with lower power consumption and higher reliability than DDR2. JEDEC began working on the DDR3 specification in June 2002, and the first DDR3 memory modules and supporting chipsets (versions of the Intel 3x series) were released for Intel-based systems in mid-2007. Due to initial high cost and limited support, DDR3 didn’t start to become popular until late 2008 when Intel released the Core i7 processor, which included an integrated tri-channel DDR3 memory controller. In early 2009, popularity increased when AMD released Socket AM3 versions of the Phenom II, the first from AMD to support DDR3. In 2009, with full support from both Intel and AMD, DDR3 finally began to achieve price parity with DDR2, causing DDR3 to begin to eclipse DDR2 in sales.

DDR3 modules use advanced signaling techniques, including self-driver calibration and data synchronization, along with an optional onboard thermal sensor. DDR3 memory runs on only 1.5V,
which is nearly 20% less than the 1.8V that DDR2 memory uses. The lower voltage combined with higher efficiency reduces overall power consumption by up to 30% compared to DDR2.

The 240-pin DDR3 modules are similar in pin count, size, and shape to the DDR2 modules; however, the DDR3 modules are incompatible with the DDR2 circuits and are designed with different keying to make them physically noninterchangeable.

DDR3 modules are available in speeds of 800MHz (effective) and higher. Just as with DDR and DDR2, the true clock speed is half the effective rate, which is technically expressed in million transfers per second (MTps). Table 6.9 shows the JEDEC-approved DDR3 module types and bandwidth specifications.

### Table 6.9 JEDEC Standard DDR3 Module (240-Pin DIMM) Speeds and Transfer Rates

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Chip Type</th>
<th>Base Clock Speed</th>
<th>Cycle Time</th>
<th>Cycles per Clock</th>
<th>Bus Width</th>
<th>Module Transfer Rate</th>
<th>Dual-Channel Transfer Rate</th>
<th>Tri-Channel Transfer Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC3-6400 DDR3-800</td>
<td>400MHz</td>
<td>2.50ns</td>
<td>2</td>
<td>800MTps</td>
<td>8 bytes</td>
<td>6,400MBps</td>
<td>12,800MBps</td>
<td>19,200MBps</td>
</tr>
<tr>
<td>PC3-8500 DDR3-1066</td>
<td>533MHz</td>
<td>1.88ns</td>
<td>2</td>
<td>1,066MTps</td>
<td>8 bytes</td>
<td>8,533MBps</td>
<td>17,066MBps</td>
<td>25,600MBps</td>
</tr>
<tr>
<td>PC3-10600 DDR3-1333</td>
<td>667MHz</td>
<td>1.50ns</td>
<td>2</td>
<td>1,333MTps</td>
<td>8 bytes</td>
<td>10,667MBps</td>
<td>21,333MBps</td>
<td>32,000MBps</td>
</tr>
<tr>
<td>PC3-12800 DDR3-1600</td>
<td>800MHz</td>
<td>1.25ns</td>
<td>2</td>
<td>1,600MTps</td>
<td>8 bytes</td>
<td>12,800MBps</td>
<td>25,600MBps</td>
<td>38,400MBps</td>
</tr>
<tr>
<td>PC3-14900 DDR3-1866</td>
<td>933MHz</td>
<td>1.07ns</td>
<td>2</td>
<td>1,866MTps</td>
<td>8 bytes</td>
<td>14,933MBps</td>
<td>29,866MBps</td>
<td>44,800MBps</td>
</tr>
<tr>
<td>PC3-17000 DDR3-2133</td>
<td>1066MHz</td>
<td>0.94ns</td>
<td>2</td>
<td>2,133MTps</td>
<td>8 bytes</td>
<td>17,066MBps</td>
<td>34,133MBps</td>
<td>51,200MBps</td>
</tr>
</tbody>
</table>

*DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)*

The fastest official JEDEC-approved standard is DDR3-2133, which is composed of chips that run at an effective speed of 2,133MHz (really megatransfers per second), resulting in modules designated PC3-17000 and having a bandwidth of 17,066MBps. However, just as with DDR and DDR2, many manufacturers produce nonstandard modules designed for overclocked systems. These are sold as modules with unofficial designations, clock speeds, and performance figures that exceed the standard ratings.

Table 6.10 shows the popular unofficial DDR3 speed ratings I’ve seen on the market. Note that because the speeds of these modules don’t conform to the standard default motherboard and chipset speeds, you won’t see an advantage to using them unless you are overclocking your system and your motherboard supports the corresponding overclocked processor and memory settings that these modules require. In addition, because these modules use standard-speed chips that are running overclocked, they almost always require custom voltage settings that are higher than the 1.5V that standard DDR3 memory uses. For system stability, I generally don’t recommend using overclocked (higher voltage) memory, instead preferring to use only that which runs on the DDR3 standard 1.5V.
Table 6.10  Overclocked (Non-JEDEC) DDR3 Module (240-Pin DIMM) Speeds and Transfer Rates

<table>
<thead>
<tr>
<th>Module Standard</th>
<th>Chip Type</th>
<th>Clock Speed (MHz)</th>
<th>Cycles per Clock</th>
<th>Bus Speed (MTps)</th>
<th>Bus Width (Bytes)</th>
<th>Transfer Rate (MBps)</th>
<th>Dual-Channel Transfer Rate (MBps)</th>
<th>Tri-Channel Transfer Rate (MBps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC3-11000</td>
<td>DDR3-1375</td>
<td>688</td>
<td>2</td>
<td>1375</td>
<td>8</td>
<td>11,000</td>
<td>22,000</td>
<td>33,000</td>
</tr>
<tr>
<td>PC3-13000</td>
<td>DDR3-1625</td>
<td>813</td>
<td>2</td>
<td>1625</td>
<td>8</td>
<td>13,000</td>
<td>26,000</td>
<td>39,000</td>
</tr>
<tr>
<td>PC3-14400</td>
<td>DDR3-1800</td>
<td>900</td>
<td>2</td>
<td>1800</td>
<td>8</td>
<td>14,400</td>
<td>28,800</td>
<td>43,200</td>
</tr>
<tr>
<td>PC3-14900</td>
<td>DDR3-1866</td>
<td>933</td>
<td>2</td>
<td>1866</td>
<td>8</td>
<td>14,933</td>
<td>29,866</td>
<td>44,800</td>
</tr>
<tr>
<td>PC3-15000</td>
<td>DDR3-1866</td>
<td>933</td>
<td>2</td>
<td>1866</td>
<td>8</td>
<td>14,933</td>
<td>29,866</td>
<td>44,800</td>
</tr>
<tr>
<td>PC3-16000</td>
<td>DDR3-2000</td>
<td>1000</td>
<td>2</td>
<td>2000</td>
<td>8</td>
<td>16,000</td>
<td>32,000</td>
<td>48,000</td>
</tr>
</tbody>
</table>

DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)

Typically, you can find DDR3 modules rated CL 5 through CL 10.

**DDR4 SDRAM**

DDR4 is the most recent JEDEC memory standard. It enables higher levels of performance along with lower power consumption and higher reliability than DDR3 does. JEDEC began working on the DDR4 specification in 2005, with the final specification published in September 2012. Samsung produced the first prototype DDR4 modules in late 2010 and released the first sample 16GB DDR4 module in July 2012. The first motherboards supporting DDR4 memory were released in August 2014, using Intel’s X99 chipset.

DDR4 modules use a Pseudo Open Drain (POD) interface (previously used in high-performance graphic DRAM) and run on a lower 1.2V voltage (compared to 1.5V for DDR3). This enables DDR4 modules to consume about 40% less power overall than previous DDR3 modules, thus saving energy while also producing less heat. DDR4 also supports write Cyclic Redundancy Check (CRC) to improve system reliability.

288-pin DDR4 modules are 1mm longer and 1mm taller than 240-pin DDR3/DDR2 modules. This was accomplished by making the individual pins only 0.85mm wide, versus the 1mm wide pins used on previous modules. DDR4 modules also feature a slight curvature about halfway between each edge and the center notch, making the outside pins shorter than the pins nearer the center notch for easier installation. Because of the different size and signaling used, DDR4 modules are both physically and electrically incompatible with previous memory module and socket designs (see Figure 6.5).

DDR4 modules are available in speeds of 1,600MHz (effective) and higher, with speeds of up to 3,200MHz (effective) expected in the future. Just as with DDR, DDR2, and DDR3 the true clock speed is half the effective rate, which is technically expressed in million transfers per second (MTps). Table 6.11 shows the official JEDEC-approved DDR4 module types and bandwidth specifications.
FIGURE 6.5 A typical 8GB DDR4 module without heat spreaders.

Table 6.11 JEDEC Standard DDR4 Module (260-Pin DIMM) Speeds and Transfer Rates

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Chip Type</th>
<th>Base Clock Speed</th>
<th>Cycle Time</th>
<th>Cycles per Clock</th>
<th>Bus Speed</th>
<th>Bus Width</th>
<th>Module Transfer Rate</th>
<th>Dual-Channel Transfer Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC4-12800</td>
<td>DDR4-1600</td>
<td>800MHz</td>
<td>1.25ns</td>
<td>2</td>
<td>1,600MTps</td>
<td>8 bytes</td>
<td>12,800MBps</td>
<td>25,600MBps</td>
</tr>
<tr>
<td>PC4-14900</td>
<td>DDR4-1866</td>
<td>933MHz</td>
<td>1.07ns</td>
<td>2</td>
<td>1,866MTps</td>
<td>8 bytes</td>
<td>14,933MBps</td>
<td>29,866MBps</td>
</tr>
<tr>
<td>PC4-17000</td>
<td>DDR4-2133</td>
<td>1066MHz</td>
<td>0.94ns</td>
<td>2</td>
<td>2,133MTps</td>
<td>8 bytes</td>
<td>17,066MBps</td>
<td>34,133MBps</td>
</tr>
<tr>
<td>PC4-19200</td>
<td>DDR4-2400</td>
<td>1,200MHz</td>
<td>0.83ns</td>
<td>2</td>
<td>2,400MTps</td>
<td>8 bytes</td>
<td>19,200MBps</td>
<td>38,400MBps</td>
</tr>
<tr>
<td>PC4-21300</td>
<td>DDR4-2666</td>
<td>1,333MHz</td>
<td>0.75ns</td>
<td>2</td>
<td>2,666MTps</td>
<td>8 bytes</td>
<td>21,333MBps</td>
<td>42,666MBps</td>
</tr>
<tr>
<td>PC4-25600</td>
<td>DDR4-3200</td>
<td>1,600MHz</td>
<td>0.63ns</td>
<td>2</td>
<td>3,200MTps</td>
<td>8 bytes</td>
<td>25,600MBps</td>
<td>51,200MBps</td>
</tr>
</tbody>
</table>

DDR = Double data rate  
MHz = Million cycles per second  
MTps = Million transfers per second  
MBps = Million bytes per second  
ns = Nanoseconds (billionths of a second)

The topology of DDR4 is technically not a bus as was used in the DDR3 and earlier memory standards. DDR4 uses a point-to-point connection instead, where each channel in the memory controller is connected to a single module.

Typically, you can find DDR4 modules rated CL12 through CL16.

RDRAM

Rambus DRAM (RDRAM) was a proprietary (non-JEDEC) memory technology found mainly in certain Intel-based Pentium III and 4 systems from 2000 through 2002. Very few of these systems are still in use today.

For more information about RDRAM and RIMM modules, see Chapter 6, “Memory,” in *Upgrading and Repairing PCs*, 19th Edition.

Memory Modules

Originally, PCs had memory installed via individual chips. They are often referred to as *dual inline package (DIP)* chips because of their physical designs. The original IBM XT and AT systems had 36 sockets on the motherboard for these individual chips, and more sockets could often be found on
memory cards plugged into the bus slots. I remember spending hours populating boards with these chips, which was a tedious job.

Besides being a time-consuming and labor-intensive way to deal with memory, DIP chips had one notorious problem—they crept out of their sockets over time as the system went through thermal cycles. Every day, when you powered the system on and off, the system heated and cooled and the chips gradually walked their way out of the sockets—a phenomenon called chip creep. Eventually, good contact was lost and memory errors resulted. Fortunately, reseating all the chips back in their sockets usually rectified the problem, but that method was labor intensive if you had many systems to support.

The alternative to this at the time was to have the memory soldered into either the motherboard or an expansion card. This prevented the chips from creeping and made the connections more permanent, but it caused another problem. If a chip did go bad, you had to attempt desoldering the old one and resoldering a new one or resort to scrapping the motherboard or memory card on which the chip was installed. This was expensive and made memory troubleshooting difficult.

A chip was needed that was both soldered and removable, which was made possible by using memory modules instead of individual chips. Early modules had one row of electrical contacts and were called single inline memory modules (SIMMs), whereas later modules had two rows and were called dual inline memory modules (DIMMs) or Rambus inline memory modules (RIMMs). These small boards plug into special connectors on a motherboard or memory card. The individual memory chips are soldered to the module, so removing and replacing them is impossible. Instead, you must replace the entire module if any part of it fails. The module is treated as though it were one large memory chip.

Several types of SIMMs, DIMMs, and RIMMs have been commonly used in desktop systems. The various types are often described by their pin count, memory row width, or memory type.

SIMMs, for example, are available in two main physical types—30-pin (8 bits plus an option for 1 additional parity bit) and 72-pin (32 bits plus an option for 4 additional parity bits)—with various capacities and other specifications. The 30-pin SIMMs are physically smaller than the 72-pin versions, and either version can have chips on one or both sides. SIMMs were widely used from the late 1980s to the late 1990s but have become obsolete.

DIMMs are available in five main types. SDR (single data rate) DIMMs have 168 pins, one notch on either side, and two notches along the contact area. DDR DIMMs, on the other hand, have 184 pins, two notches on each side, and only one offset notch along the contact area. DDR2 and DDR3 DIMMs have 240 pins, two notches on each side, and one near the center of the contact area. DDR4 DIMMs have 288 pins, two notches on each side (the notches are more squared off than with previous DIMM designs), and one near the center of the contact area. All DIMMs are either 64 bits (non-ECC/parity) or 72 bits (data plus parity or error-correcting code [ECC]) wide. The main physical difference between SIMMs and DIMMs is that DIMMs have different signal pins on each side of the module, resulting in two rows of electrical contacts. That is why they are called dual inline memory modules, and why with only 1 inch of additional length, they have many more pins than a SIMM.

Note

There is confusion among users and even in the industry regarding the terms single-sided and double-sided with respect to memory modules. In truth, the single- or doublesided designation actually has nothing to do with whether chips are physically located on one or both sides of the module, and it has nothing to do with whether the module is a SIMM or DIMM (meaning whether the connection pins are single- or double-inline). Instead, the terms single-sided and double-sided indicate whether the module has one or two internal banks (called ranks) of memory chips installed.
A dual-rank DIMM module has two complete 64-bit wide banks of chips logically stacked so that the module is twice as deep (has twice as many 64-bit rows). In most (but not all) cases, this requires chips to be on both sides of the module, therefore, the term **double-sided** often indicates that a module has two ranks, even though the term is technically incorrect. Single-rank modules (incorrectly referred to as single-sided) can also have chips physically mounted on both sides of the module, and dual-rank modules can have chips physically mounted on only one side. I recommend using the terms **single rank** or **dual rank** instead, because they are much more accurate and easily understood.

Figures 6.6 through 6.13 show a typical 30-pin (8-bit) SIMM, 72-pin (32-bit) SIMM, 168-pin SDRAM DIMM, 184-pin DDR SDRAM (64-bit) DIMM, 240-pin DDR2 DIMM, 240-pin DDR3 DIMM, 288-pin DDR4 DIMM, and 184-pin RIMM, respectively. The pins are numbered from left to right and are connected to both sides of the module on the SIMMs. The pins on the DIMM are different on each side, but on a SIMM, each side is the same as the other and the connections carry through. Note that all dimensions are in both inches and millimeters (in parentheses), and modules are generally available in ECC versions with 1 extra ECC (or parity) bit for every 8 data bits (multiples of 9 in data width) or versions that do not include ECC support (multiples of 8 in data width).

**FIGURE 6.6** A typical 30-pin SIMM.

**FIGURE 6.7** A typical 72-pin SIMM.
FIGURE 6.8  A typical 168-pin SDRAM DIMM.

FIGURE 6.9  A typical 184-pin DDR DIMM.

FIGURE 6.10  A typical 240-pin DDR2 DIMM.
FIGURE 6.11  A typical 240-pin DDR3 DIMM.

FIGURE 6.12  A typical 288-pin DDR4 DIMM.
FIGURE 6.13 A typical 184-pin RIMM (RIMM modules use RDRAM).

All these memory modules are fairly compact considering the amount of memory they hold and are available in several capacities and speeds. Table 6.12 lists the various capacities available for SIMMs, DIMMs, and RIMMs.

Table 6.12 SIMM, DIMM, and RIMM Capacities

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Standard Depth×Width</th>
<th>Parity/ECC Depth×Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-Pin SIMM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>256KB</td>
<td>256K×8</td>
<td>256K×9</td>
</tr>
<tr>
<td>1MB</td>
<td>1M×8</td>
<td>1M×9</td>
</tr>
<tr>
<td>4MB</td>
<td>4M×8</td>
<td>4M×9</td>
</tr>
<tr>
<td>16MB</td>
<td>16M×8</td>
<td>16M×9</td>
</tr>
<tr>
<td>72-Pin SIMM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1MB</td>
<td>256K×32</td>
<td>256K×36</td>
</tr>
<tr>
<td>2MB</td>
<td>512K×32</td>
<td>512K×36</td>
</tr>
<tr>
<td>4MB</td>
<td>1M×32</td>
<td>1M×36</td>
</tr>
<tr>
<td>8MB</td>
<td>2M×32</td>
<td>2M×36</td>
</tr>
<tr>
<td>16MB</td>
<td>4M×32</td>
<td>4M×36</td>
</tr>
<tr>
<td>32MB</td>
<td>8M×32</td>
<td>8M×36</td>
</tr>
<tr>
<td>64MB</td>
<td>16M×32</td>
<td>16M×36</td>
</tr>
<tr>
<td>128MB</td>
<td>32M×32</td>
<td>32M×36</td>
</tr>
<tr>
<td>168/184-Pin DIMM/DDR DIMM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8MB</td>
<td>1M×64</td>
<td>1M×72</td>
</tr>
<tr>
<td>16MB</td>
<td>2M×64</td>
<td>2M×72</td>
</tr>
<tr>
<td>32MB</td>
<td>4M×64</td>
<td>4M×72</td>
</tr>
<tr>
<td>64MB</td>
<td>8M×64</td>
<td>8M×72</td>
</tr>
</tbody>
</table>
Memory modules of each type and capacity are available in various speed ratings. Consult your motherboard documentation for the correct memory speed and type for your system. If a system requires a specific speed memory module, you can almost always substitute faster speeds if the one specified is not available. Generally, no problems occur in mixing module speeds, as long as you use modules equal to or faster than what the system requires. Because there’s little price difference between the various speed versions, I often buy faster modules than are necessary for a particular application, especially if they are the same price as slower modules. This might make them more usable in a future system that could require the faster speed.

Because SDRAM and newer modules have an onboard SPD ROM that reports their speed and timing parameters to the system, most systems run the memory controller and memory bus at the speed matching the slowest module installed.

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Standard Depth×Width</th>
<th>Parity/ECC Depth×Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>128MB</td>
<td>16M×64</td>
<td>16M×72</td>
</tr>
<tr>
<td>256MB</td>
<td>32M×64</td>
<td>32M×72</td>
</tr>
<tr>
<td>512MB</td>
<td>64M×64</td>
<td>64M×72</td>
</tr>
<tr>
<td>1,024MB</td>
<td>128M×64</td>
<td>128M×72</td>
</tr>
<tr>
<td>2,048MB</td>
<td>256M×64</td>
<td>256M×72</td>
</tr>
<tr>
<td><strong>240-Pin DDR2/DDR3 DIMM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>256MB</td>
<td>32M×64</td>
<td>32M×72</td>
</tr>
<tr>
<td>512MB</td>
<td>64M×64</td>
<td>64M×72</td>
</tr>
<tr>
<td>1,024MB</td>
<td>128M×64</td>
<td>128M×72</td>
</tr>
<tr>
<td>2,048MB</td>
<td>256M×64</td>
<td>256M×72</td>
</tr>
<tr>
<td>4,096MB</td>
<td>512M×64</td>
<td>512M×72</td>
</tr>
<tr>
<td>8,192MB</td>
<td>1,024M×64</td>
<td>1,024M×72</td>
</tr>
<tr>
<td><strong>288-Pin DDR4 DIMM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4,096MB</td>
<td>512M×64</td>
<td>512M×72</td>
</tr>
<tr>
<td>8,192MB</td>
<td>1,024M×64</td>
<td>1,024M×72</td>
</tr>
<tr>
<td><strong>184-Pin RIMM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>64MB</td>
<td>32M×16</td>
<td>32M×18</td>
</tr>
<tr>
<td>128MB</td>
<td>64M×16</td>
<td>64M×18</td>
</tr>
<tr>
<td>256MB</td>
<td>128M×16</td>
<td>128M×18</td>
</tr>
<tr>
<td>512MB</td>
<td>256M×16</td>
<td>256M×18</td>
</tr>
<tr>
<td>1,024MB</td>
<td>512M×16</td>
<td>512M×18</td>
</tr>
</tbody>
</table>

*Higher capacities are available for servers*
Note
A bank is the smallest amount of memory needed to form a single row of memory addressable by the processor. It is the minimum amount of physical memory that the processor reads or writes at one time and usually corresponds to the data bus width of the processor. If a processor has a 64-bit data bus, a bank of memory also is 64 bits wide. If the memory runs dual- or tri-channel, a virtual bank is formed that is two or three times the absolute data bus width of the processor.

You can’t always replace a module with a higher-capacity unit and expect it to work. Systems might have specific design limitations for the maximum capacity of module they can take. A larger-capacity module works only if the motherboard is designed to accept it in the first place. Consult your system documentation to determine the correct capacity and speed to use. With some systems, a BIOS update might enable the use of higher-capacity and/or faster modules than the system was originally designed to use. Check with the system vendor to see whether a BIOS update is available.

Registered Modules
SDRAM through DDR4 modules are available in unbuffered and registered versions. Most PC motherboards are designed to use unbuffered modules, which enable the memory controller signals to pass directly to the memory chips on the module with no interference. This is not only the cheapest design, but also the fastest and most efficient. The only drawback is that the motherboard designer must place limits on how many modules (meaning module sockets) can be installed on the board, and it could limit how many chips can be on a module. So-called double-sided modules that really have multiple banks of chips onboard might be restricted on some systems in certain combinations.

Systems designed to accept extremely large amounts of RAM (such as servers) often require registered modules. A registered module uses an architecture that has register chips on the module that act as an interface between the actual RAM chips and the chipset. The registers temporarily hold data passing to and from the memory chips and enable many more RAM chips to be driven or otherwise placed on the module than the chipset could normally support. This enables motherboard designs that can support many modules and enables each module to have a larger number of chips. In general, registered modules are required by server or workstation motherboards designed to support more than four sockets. One anomaly is the initial version of the AMD Athlon 64 FX processor, which also uses registered memory because its Socket 940 design was based on the AMD Opteron workstation and server processor. Subsequent Socket 939, AM2, AM2+, AM3, and AM3+ versions of the Athlon FX no longer require registered memory.

To provide the space needed for the buffer chips, a registered DIMM is often taller than a standard DIMM. Figure 6.14 compares a typical registered DIMM to a typical unbuffered DIMM.

Tip
If you are installing registered DIMMs in a slimline case, clearance between the top of the DIMM and the case might be a problem. Some vendors sell low-profile registered DIMMs that are about the same height as unbuffered DIMMs. Use this type of DIMM if your system does not have enough head room for standard registered DIMMs. Some vendors sell only this type of DIMM for particular systems.

The important thing to note is that you can use only the type of module your motherboard (or chipset) is designed to support. For most, that is standard unbuffered modules or, in some cases, registered modules.
FIGURE 6.14  A typical registered DIMM is taller than a typical unbuffered DIMM to provide room for buffer chips.

SDR DIMM Details

SDR DIMMs use a completely different type of presence detect than SIMMs, called serial presence detect (SPD). It consists of a small EEPROM or flash memory chip on the DIMM that contains specially formatted data indicating the DIMM’s features. This serial data can be read via the serial data pins on the DIMM, and it enables the motherboard to autoconfigure to the exact type of DIMM installed.

DIMMs can come in several varieties, including unbuffered and buffered as well as 3.3V and 5V. Buffered DIMMs have additional buffer chips on them to interface to the motherboard. Unfortunately, these buffer chips slow down the DIMM and are not effective at higher speeds. For this reason, PC systems (those that do not use registered DIMMs) use only unbuffered 3.5V DIMMs. The voltage is simple—DIMM designs for PCs are almost universally 3.3V. If you install a 5V DIMM in a 3.3V socket, it would be damaged, but keying in the socket and on the DIMM prevents that.

Apple and other non-PC systems can use the buffered 5V versions. Fortunately, the key notches along the connector edge of a DIMM are spaced differently for buffered/unbuffered and 3.3V/5V DIMMs, as shown in Figure 6.15. This prevents inserting a DIMM of the wrong type into a given socket.

FIGURE 6.15  The 168-pin DRAM DIMM notch key definitions.
**DDR DIMM Details**

The 184-pin DDR DIMMs use a single key notch to indicate voltage, as shown in Figure 6.16.

![184-Pin DDR DIMM](image)

**FIGURE 6.16** The 184-pin DDR SDRAM DIMM keying.

DDR DIMMs also use two notches on each side to enable compatibility with both low- and high-profile latched sockets. Note that the key position is offset with respect to the center of the DIMM to prevent inserting it backward in the socket. The key notch is positioned to the left, centered, or to the right of the area between pins 52 and 53. This indicates the I/O voltage for the DDR DIMM and prevents installing the wrong type into a socket that might damage the DIMM.

**DDR2 DIMM Details**

The 240-pin DDR2 DIMMs use two notches on each side to enable compatibility with both low- and high-profile latched sockets. The connector key is offset with respect to the center of the DIMM to prevent inserting it backward in the socket. The key notch is positioned in the center of the area between pins 64 and 65 on the front (184/185 on the back), and there is no voltage keying because all DDR2 DIMMs run on 1.8V.

**DDR3 DIMM Details**

The 240-pin DDR3 DIMMs use two notches on each side to enable compatibility with both low- and high-profile latched sockets. The connector key is offset with respect to the center of the DIMM to prevent inserting it backward in the socket. The key notch is positioned in the center of the area between pins 48 and 49 on the front (168/169 on the back), and there is no voltage keying because all DDR3 DIMMs run on 1.5V.

**DDR4 DIMM Details**

The 288-pin DDR4 DIMMs use two notches on each side to enable compatibility with both low- and high-profile latched sockets. The notches use a more squared-off shape than with previous designs. The connector key is offset with respect to the center of the DIMM to prevent inserting it backward in the socket. The key notch is positioned in the center of the area between pins 77 and 78 on the front, and there is no voltage keying because all DDR4 DIMMs run on 1.2V.
Determining a Memory Module’s Size and Features

Most memory modules are labeled with a sticker indicating the module’s type, speed rating, and manufacturer. If you are attempting to determine whether existing memory can be used in a new computer, or if you need to replace memory in an existing computer, this information can be essential. Figure 6.17 compares the markings on a 512MB DDR2 module from Crucial Technology and a 2GB DDR2 module from Kingston Technology.

![Markings on a 512MB DDR2 module (top) from Crucial Technology compared to markings on a 2GB (bottom) DDR2 memory module from Kingston Technology.](image)

However, if you have memory modules that are not labeled, you can still determine the module type, speed, and capacity if the memory chips on the module are clearly labeled. For example, assume you have a memory module with chips labeled as follows:

MT46V64M8TG-75

By using an Internet search engine such as Google and entering the number from one of the memory chips, you can usually find the data sheet for the memory chips. Consider the following example: Say you have a registered memory module and want to look up the part number for the memory chips (usually eight or more chips) rather than the buffer chips on the module (usually from one to three, depending on the module design). In this example, the part number turns out to be a Micron memory chip that decodes like this:

MT = Micron Technologies (the memory chip maker)
46 = DDR SDRAM
V = 2.5V DC
64M8 = 8 million rows × 8 (equals 64) × 8 banks (often written as 64 Meg × 8)
TG = 66-pin TSOP chip package
–75 = 7.5ns @ CL2 latency (DDR 266)
The full datasheet for this example is located at http://download.micron.com/pdf/datasheets/dram/ddr/512MBDDRx4x8x16.pdf.

From this information, you can determine that the module has the following characteristics:

- The module runs at DDR266 speeds using standard 2.5V DC voltage.
- The module has a latency of CL2, so you can use it on any system that requires CL2 or slower latency (such as CL2.5 or CL3).
- Each chip has a capacity of 512Mb (64 × 8 = 512).
- Each chip contains 8 bits. Because it takes 8 bits to make 1 byte, you can calculate the capacity of the module by grouping the memory chips on the module into groups of eight. If each chip contains 512Mb, a group of eight means that the module has a size of 512Mb × 8 = 512MB. A dual-bank module has two groups of eight chips for a capacity of 1GB (512Mb × 8 = 1024MB, or 1GB).

If the module has nine instead of eight memory chips (or 18 instead of 16), the additional chips are used for parity checking and support ECC error correction on servers with this feature.

To determine the size of the module in megabytes or gigabytes and to determine whether the module supports ECC, count the memory chips on the module and compare them to Table 6.13. Note that the size of each memory chip in megabits is the same as the size in megabytes if the memory chips use an 8-bit design.

<table>
<thead>
<tr>
<th>Number of Chips</th>
<th>Number of Bits in Each Bank</th>
<th>Module Size</th>
<th>Supports ECC?</th>
<th>Single or Dual Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>64</td>
<td>512MB</td>
<td>No</td>
<td>Single</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
<td>512MB</td>
<td>Yes</td>
<td>Single</td>
</tr>
<tr>
<td>16</td>
<td>64</td>
<td>1GB</td>
<td>No</td>
<td>Dual</td>
</tr>
<tr>
<td>18</td>
<td>72</td>
<td>1GB</td>
<td>Yes</td>
<td>Dual</td>
</tr>
</tbody>
</table>

The additional chip that each group of eight chips uses provides parity checking, which the ECC function employs on most server motherboards to correct single-bit errors.

A registered module contains 9 or 18 memory chips for ECC plus additional memory buffer chips. These chips are usually smaller in size and located near the center of the module, as shown previously in Figure 6.10.

**Note**

Some modules use 16-bit wide memory chips. In such cases, only 4 chips are needed for single-bank memory (5 with parity/ECC support), and 8 are needed for double-bank memory (10 with parity/ECC support). These memory chips use a design listed as capacity times 16, like this: 256Mb × 16.
You can also see this information if you look up the manufacturer and the memory type in a search engine. For example, a web search for “Micron Unbuffered DIMM Design” locates a table showing various DIMM organization, SDRAM density, and other information for listed modules.

As you can see, with a little detective work, you can determine the size, speed, and type of a memory module—even if the module isn’t marked—as long as the markings on the memory chips themselves are legible.

**Tip**

If you are unable to decipher a chip part number, you can use a program, such as CPU-Z (www.cpuid.com) or HWINFO (www.hwinfo.com) to identify your memory module, as well as many other facts about your computer, including chipset, processor, empty memory sockets, and much more.

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**Memory Banks**

Memory chips (DIPs, SIMMs, SIPPs, and DIMMs) are organized in banks on motherboards and memory cards. You should know the memory bank layout and position on the motherboard and memory cards.

You need to know the bank layout when adding memory to the system. In addition, memory diagnostics report error locations by byte and bit addresses, and you must use these numbers to locate which bank in your system contains the problem.

The banks usually correspond to the data bus capacity of the system’s microprocessor. Table 6.14 shows the widths of individual banks based on the type of PC.

**Table 6.14 Memory Bank Widths on Various Systems**

<table>
<thead>
<tr>
<th>Processor</th>
<th>Data Bus</th>
<th>Memory Bank Width</th>
<th>Memory Bank Width (Parity/ECC)</th>
<th>30-Pin SIMMs per Bank</th>
<th>72-Pin SIMMs per Bank</th>
<th>DIMMs per Bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>8088</td>
<td>8-bit</td>
<td>8 bits</td>
<td>9 bits</td>
<td>1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>8086</td>
<td>16-bit</td>
<td>16 bits</td>
<td>18 bits</td>
<td>2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>286</td>
<td>16-bit</td>
<td>16 bits</td>
<td>18 bits</td>
<td>2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>386SX, SL, SLC</td>
<td>16-bit</td>
<td>16 bits</td>
<td>18 bits</td>
<td>2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>486SLC, SLC2</td>
<td>16-bit</td>
<td>16 bits</td>
<td>18 bits</td>
<td>2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>386DX</td>
<td>32-bit</td>
<td>32 bits</td>
<td>36 bits</td>
<td>4</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>486SX, DX, DX2, DX4, 5x86</td>
<td>32-bit</td>
<td>32 bits</td>
<td>36 bits</td>
<td>4</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>x86 and x86-64 running single-channel mode</td>
<td>64-bit</td>
<td>64 bits</td>
<td>72 bits</td>
<td>—</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>x86 and x86-64 running dual-channel mode</td>
<td>64-bit</td>
<td>128 bits</td>
<td>144 bits</td>
<td>—</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>x86 and x86-64 running tri-channel mode</td>
<td>64-bit</td>
<td>192 bits</td>
<td>216 bits</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
</tbody>
</table>
DIMMs are ideal for Pentium (and higher) systems because the 64-bit width of the DIMM exactly matches the 64-bit width of the Pentium processor data bus. Therefore, each DIMM represents an individual bank, and these can be added or removed one at a time. Many recent systems have been designed to use matched pairs or triples of memory modules for faster performance. So-called “dual-channel” and “tri-channel” designs treat two or three matched modules as a single bank of memory.

The physical orientation and numbering of the SIMMs or DIMMs used on a motherboard are arbitrary and determined by the board’s designers, so documentation covering your system or card comes in handy. You can determine the layout of a motherboard or an adapter card through testing, but that takes time and might be difficult, particularly after you have a problem with a system.

**Caution**

If your system supports dual- or tri-channel memory, be sure you use the correct memory sockets to enable multichannel operation. Check the documentation to ensure that you use the correct sockets. Most multichannel systems still run in single-channel mode if the memory is not installed in a way that permits full multichannel operation, but performance is lower than if the memory were installed properly. Some systems provide dual-channel support if an odd number of modules is installed, as long as the total capacity of two modules installed in one channel equals the size of the single module in the other channel and all modules are the same speed and latency. Again, check your documentation for details.

**Memory Module Speed**

When you replace a failed memory module or install a new module as an upgrade, you typically must install a module of the same type and speed as the others in the system. You can substitute a module with a different (faster) speed, but only if the replacement module’s speed is equal to or faster than that of the other modules in the system.

Some people have had problems when “mixing” modules of different speeds. With the variety of motherboards, chipsets, and memory types, few ironclad rules exist. When in doubt as to which speed module to install in your system, consult the motherboard documentation for more information.

Substituting faster memory of the same type doesn’t result in improved performance if the system still operates the memory at the same speed. Systems that use DIMMs or RIMMs can read the speed and timing features of the module from a special SPD ROM installed on the module and then set chipset (memory controller) timing accordingly. In these systems, you might see an increase in performance by installing faster modules, to the limit of what the chipset supports.

To place more emphasis on timing and reliability, some Intel and JEDEC standards governing memory types require certain levels of performance. These standards certify that memory modules perform within Intel’s timing and performance guidelines.

The same common symptoms result when the system memory has failed or is simply not fast enough for the system’s timing. The usual symptoms are frequent parity check errors or a system that does not operate. The POST might report errors, too. If you’re unsure of which chips to buy for your system, contact the system manufacturer or a reputable chip supplier.

► See “Parity Checking,” p. 390.

**Parity and ECC**

Part of the nature of memory is that it inevitably fails. These failures are usually classified as two basic types: hard fails and soft errors.
The best understood are hard fails, in which the chip is working and then, because of some flaw, physical damage, or other event, becomes damaged and experiences a permanent failure. Fixing this type of failure normally requires replacing some part of the memory hardware, such as the chip, SIMM, or DIMM. Hard error rates are known as HERs.

The other, more insidious type of failure is the soft error, which is a nonpermanent failure that might never recur or could occur only at infrequent intervals. Soft error rates are known as SERs.

In the late 1970s, Intel made a discovery about soft errors that shook the memory industry. It found that alpha particles were causing an unacceptably high rate of soft errors or single event upsets (SEUs) in the 16KB DRAMs that were available at the time. Because alpha particles are low-energy particles that can be stopped by something as thin and light as a sheet of paper, it became clear that for alpha particles to cause a DRAM soft error, they would have to be coming from within the semiconductor material. Testing showed trace elements of thorium and uranium in the plastic and ceramic chip packaging materials used at the time. This discovery forced all the memory manufacturers to evaluate their manufacturing processes to produce materials free from contamination.

Today, memory manufacturers have all but totally eliminated the alpha-particle source of soft errors, and more recent discoveries prove that alpha particles are now only a small fraction of the cause of DRAM soft errors.

As it turns out, the biggest cause of soft errors today is cosmic rays. IBM researchers began investigating the potential of terrestrial cosmic rays in causing soft errors similar to alpha particles. The difference is that cosmic rays are high-energy particles and can’t be stopped by sheets of paper or other more powerful types of shielding. The leader in this line of investigation was Dr. J.F. Ziegler of the IBM Watson Research Center in Yorktown Heights, New York. He has produced landmark research into understanding cosmic rays and their influence on soft errors in memory. One interesting set of experiments found that cosmic ray–induced soft errors were eliminated when the DRAMs were moved to an underground vault shielded by more than 50 feet of rock.

Cosmic ray–induced errors are even more of a problem in SRAMs than DRAMS because the amount of charge required to flip a bit in an SRAM cell is less than is required to flip a DRAM cell capacitor. Cosmic rays are also more of a problem for higher-density memory. As chip density increases, it becomes easier for a stray particle to flip a bit. It has been predicted by some that the soft error rate of a 64MB DRAM is double that of a 16MB chip, and a 256MB DRAM has a rate four times higher. As memory sizes continue to increase, it’s likely that soft error rates will also increase.

Unfortunately, the PC industry has largely failed to recognize this cause of memory errors. Electrostatic discharge, power surges, and unstable software can much more easily explain away the random and intermittent nature of a soft error, especially right after a new release of an operating system (OS) or major application.

Although cosmic rays and other radiation events are perhaps the biggest cause of soft errors, soft errors can also be caused by the following:

- **Power glitches or noise on the line**—This can be caused by a defective power supply in the system or by defective power at the outlet.

- **Incorrect type or speed rating**—The memory must be the correct type for the chipset and match the system access speed.

- **RF (radio frequency) interference**—Caused by radio transmitters in close proximity to the system, which can generate electrical signals in system wiring and circuits. Keep in mind that the increased use of wireless networks, keyboards, and mouse devices can lead to a greater risk of RF interference.
Static discharges—These discharges cause momentary power spikes, which alter data.

Timing glitches—Data doesn’t arrive at the proper place at the proper time, causing errors. Often caused by improper settings in the BIOS Setup, by memory that is rated slower than the system requires, or by overclocked processors and other system components.

Heat buildup—High-speed memory modules run hotter than older modules. RDRAM RIMM modules were the first memory to include integrated heat spreaders, and many high-performance DDR, DDR2, DDR3, and DDR4 memory modules now include heat spreaders to help fight heat buildup.

Most of these problems don’t cause chips to permanently fail (although bad power or static can damage chips permanently), but they can cause momentary problems with data.

How can you deal with these errors? The best way to deal with this problem is to increase the system’s fault tolerance. This means implementing ways of detecting and possibly correcting errors in PC systems. Three basic levels and techniques are used for fault tolerance in modern PCs:

- Nonparity
- Parity
- ECC

Nonparity systems have no fault tolerance. The only reason they are used is because they have the lowest inherent cost. No additional memory is necessary, as is the case with parity or ECC techniques. Because a parity-type data byte has 9 bits versus 8 for nonparity, memory cost is approximately 12.5% higher. Also, the nonparity memory controller is simplified because it does not need the logic gates to calculate parity or ECC check bits. Portable systems that place a premium on minimizing power might benefit from the reduction in memory power resulting from fewer DRAM chips. Finally, the memory system data bus is narrower, which reduces the number of data buffers. The statistical probability of memory failures in a modern office desktop computer is now estimated at about one error every few months. Errors will be more or less frequent depending on how much memory you have.

This error rate might be tolerable for low-end systems that are not used for mission-critical applications. In this case, the extreme market sensitivity to price probably can’t justify the extra cost of parity or ECC memory, and such errors then must be tolerated.

Parity Checking

One standard IBM set for the industry is that the memory chips in a bank of nine each handle 1 bit of data: 8 bits per character plus 1 extra bit called the parity bit. The parity bit enables memory-control circuitry to keep tabs on the other 8 bits—a built-in cross-check for the integrity of each byte in the system.

Originally, all PC systems used parity-checked memory to ensure accuracy. Starting in 1994, most vendors began shipping systems without parity checking or any other means of detecting or correcting errors on-the-fly. These systems used cheaper nonparity memory modules, which saved about 10%–15% on memory costs for a system.

Parity memory results in increased initial system cost, primarily because of the additional memory bits involved. Parity can’t correct system errors, but because parity can detect errors, it can make the user aware of memory errors when they happen.

Since then, Intel, AMD, and other manufacturers have put support for ECC memory primarily in server chipsets and processors. Chipsets and processors for standard desktop or laptop systems typically lack support for either parity or ECC.
**How Parity Checking Works**

IBM originally established the odd parity standard for error checking. The following explanation might help you understand what is meant by odd parity. As the 8 individual bits in a byte are stored in memory, a parity generator/checker, which is either part of the CPU or located in a special chip on the motherboard, evaluates the data bits by adding up the number of 1s in the byte. If an even number of 1s is found, the parity generator/checker creates a 1 and stores it as the ninth bit (parity bit) in the parity memory chip. That makes the sum for all 9 bits (including the parity bit) an odd number. If the original sum of the 8 data bits is an odd number, the parity bit created would be a 0, keeping the sum for all 9 bits an odd number. The basic rule is that the value of the parity bit is always chosen so that the sum of all 9 bits (8 data bits plus 1 parity bit) is stored as an odd number. If the system used even parity, the example would be the same except the parity bit would be created to ensure an even sum. It doesn’t matter whether even or odd parity is used; the system uses one or the other, and it is completely transparent to the memory chips involved. Remember that the 8 data bits in a byte are numbered 0 1 2 3 4 5 6 7. The following examples might make it easier to understand:

<table>
<thead>
<tr>
<th>Data bit number:</th>
<th>0 1 2 3 4 5 6 7</th>
<th>Parity bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data bit value:</td>
<td>1 0 1 1 0 0 1 1</td>
<td>0</td>
</tr>
</tbody>
</table>

In this example, because the total number of data bits with a value of 1 is an odd number (5), the parity bit must have a value of 0 to ensure an odd sum for all 9 bits.

Here is another example:

<table>
<thead>
<tr>
<th>Data bit number:</th>
<th>0 1 2 3 4 5 6 7</th>
<th>Parity bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data bit value:</td>
<td>1 1 1 1 0 0 1 1</td>
<td>1</td>
</tr>
</tbody>
</table>

In this example, because the total number of data bits with a value of 1 is an even number (6), the parity bit must have a value of 1 to create an odd sum for all 9 bits.

When the system reads memory back from storage, it checks the parity information. If a (9-bit) byte has an even number of bits, that byte must have an error. The system can’t tell which bit has changed or whether only a single bit has changed. If 3 bits changed, for example, the byte still flags a parity-check error; if 2 bits changed, however, the bad byte could pass unnoticed. Because multiple bit errors (in a single byte) are rare, this scheme gives you a reasonable and inexpensive ongoing indication that memory is good or bad.

**ECC**

ECC goes a big step beyond simple parity-error detection. Instead of just detecting an error, ECC allows a single bit error to be corrected, which means the system can continue without interruption and without corrupting data. ECC, as implemented in most PCs, can only detect, not correct, double-bit errors. Because studies have indicated that approximately 98% of memory errors are the single-bit variety, the most commonly used type of ECC is one in which the attendant memory controller detects and corrects single-bit errors in an accessed data word. (Double-bit errors can be detected but not corrected.) This type of ECC is known as single-bit error-correction double-bit error detection (SEC-DED) and requires an additional 7 check bits over 32 bits in a 4-byte system and an additional 8 check bits over 64 bits in an 8-byte system. If the system uses SIMMs, two 36-bit (parity) SIMMs are added for each bank (for a total of 72 bits), and ECC is done at the bank level. If the system uses DIMMs, a single parity/ECC 72-bit DIMM is used as a bank and provides the additional bits. RIMMs are installed in singles or pairs, depending on the chipset and motherboard. They must be 18-bit versions if parity/ECC is desired.
ECC entails the memory controller calculating the check bits on a memory-write operation, performing a compare between the read and calculated check bits on a read operation, and, if necessary, correcting bad bits. The additional ECC logic in the memory controller is not very significant in this age of inexpensive, high-performance VLSI logic, but ECC actually affects memory performance on writes. This is because the operation must be timed to wait for the calculation of check bits and, when the system waits for corrected data, reads. On a partial-word write, the entire word must first be read, the affected byte(s) rewritten, and then new check bits calculated. This turns partial-word write operations into slower read-modify writes. Fortunately, this performance hit is small, on the order of a few percent at maximum, so the trade-off for increased reliability is a good one.

Most memory errors are of a single-bit nature, which ECC can correct. Incorporating this fault-tolerant technique provides high system reliability and attendant availability. An ECC-based system is a good choice for servers, workstations, or mission-critical applications in which the cost of a potential memory error outweighs the additional memory and system cost to correct it, along with ensuring that it does not detract from system reliability.

Unfortunately, most standard desktop and laptop PC processors, motherboards (chipsets), and memory modules don’t support ECC. If you want a system that supports ECC, make sure all the components involved support ECC. This usually means purchasing more expensive processors, motherboards, and RAM designed for server or high-end workstation applications.

**RAM Upgrades**

Adding memory to a system is one of the most useful upgrades you can perform and also one of the least expensive—especially when you consider the increased performance of Windows, Linux, and their applications when you give them access to more memory. In some cases, doubling the memory can practically double the speed of a computer. But it doesn’t always pay to go overboard because adding memory you don’t really need will cost money and power, and you will gain little or nothing in speed. The best philosophy to take when adding RAM to a computer is that “more is better, up to a point.”

The maximum physical memory capacity of a system is dictated by several factors. The first is the amount addressable by the processor itself, which is based on the number of physical address lines in the chip. The original PC processors (8086/8088) had 20 address lines, which resulted in those chips being able to recognize up to 1MB \((2^{20}\) bytes) of RAM. The 286/386SX increased memory addressing capability to 24 lines, making them capable of addressing 16MB \((2^{24}\) bytes). Modern x86 processors have 32–36 address lines, resulting in from 4GB to 64GB of addressable RAM. Modern x86-64 (64-bit) processors have 40 address lines, resulting in a maximum of 1TB (1 terabyte) of supported physical RAM.
If you run Windows XP, you should specify a *minimum* of 256MB, and preferably 512MB–1GB or more depending on the applications you intend to run. If you run 32-bit Windows 7/8.1/10 or Vista, the *absolute minimum* should be 512MB according to Microsoft, but I recommend a minimum of 1GB, with 2GB–3GB preferred. 64-bit versions of Windows 7 and Windows 8/8.1/10 have a 2GB minimum, but perform better with 4GB or more of memory.

Beyond having the minimum to run the OS you choose, the way you use your system, especially the applications you run, can be the major determining factor as to just how much memory is best. For example, if you are a power user with four or more displays simultaneously connected to your system, each with multiple open applications, or you run memory-intensive applications such as photo- and video-editing programs, or if you use a virtual machine manager (VMM) like Virtual PC or VMware to run multiple OSs simultaneously (each of those with open applications), you might want as much memory as you can possibly install. Many older laptops won’t accept as much memory as you might want (or need) to install, so if you upgrade an older system that uses an obsolete (and expensive) type of memory, the best tip might be to consider moving up to a newer system that can accept more memory of a mainstream type that is less expensive.

When purchasing a new system, try to get it with all the memory you need right away. Some motherboards are more limited in the number of memory sockets they contain, and some of those will already be filled when the system is delivered. This means you might need to remove some of the existing memory to add more, which makes future upgrades more expensive. The only caveat here is that I often find that I can purchase memory much more inexpensively from third-party vendors than from the system manufacturer. When purchasing a new system, check on how much the manufacturer charges for the amount of memory you want, as opposed to taking the system with the default minimum and immediately adding the desired memory yourself, purchased from a third-party memory vendor.

The following sections discuss adding memory, including selecting memory chips, installing memory chips, and testing the installation.

**Upgrade Options and Strategies**

Adding memory can be an inexpensive solution; the cost of mainstream memory is extremely low relative to other system components, and adding more memory can give your computer’s performance a big boost.

How do you add memory to your PC? You have two options, listed in order of convenience and cost:

- Adding memory in vacant slots on your motherboard
- Replacing your current motherboard’s memory with higher-capacity memory

If you decide to upgrade to a more powerful computer system or motherboard, you usually can’t salvage the memory from your previous system. Most of the time it is best to plan on equipping a new board with the optimum type of memory that it supports.

Be sure to carefully weigh your future needs for computing speed and a multitasking OS against the amount of money you spend to upgrade current equipment.

How can you tell if you have enough memory or not? The best way is to run your most demanding applications (all that would be open at the same time and with your largest datasets) and then check the memory usage using the Windows Task Manager (taskmgr.exe). With Task Manager running, click the Performance tab to see the amount of Physical Memory being used versus the total available. Under Windows 7/8.1/10 and Vista the memory usage is shown both as a percentage of the total as well as an amount.
Figure 6.18 shows the Task Manager running on a Windows 7 system reporting 18% or 2.85GB of memory being used on a system with 16GB installed. Figure 6.19 shows the Task Manager running on a Windows XP system reporting 1.63GB being used (under the misnomer “PF Usage”) on a system with about 3.5GB of RAM available (4GB minus about 0.5GB reserved by the hardware), which is about 47% of the total.

**FIGURE 6.18** Windows 7 Task Manager showing 18% or 2.85GB Physical Memory use on a system with 16GB installed.

**FIGURE 6.19** Windows XP Task Manager showing 47% or 1.63GB Physical Memory use on a system with about 3.5GB available (out of 4GB installed).
If you see the amount of physical memory being used is higher than around 80% of the total then you might consider adding more memory. In both of these examples the amount of memory installed is more than enough to run the applications that were open at the time; in fact, the system with 16GB installed would have been fine with 8GB or less.

Before you add RAM to a system (or replace defective RAM chips), you must determine the memory modules required for your system. Your system documentation has this information.

If you need to replace a defective memory module or add more memory to your system, you have several methods for determining the correct module for your system:

- Inspect the modules installed in your system. Each module has markings that indicate its capacity and speed. RAM capacity and speed were discussed in detail earlier in this chapter. You can write down the markings on the memory module and use them to determine the type of memory you need. Check with a local store or an online memory vendor for help.

- Look up your system using the online memory-configuration utility provided by your preferred memory vendor. Originally, these configuration utilities were primarily for users of name-brand systems. However, most vendors have now added major motherboard brands and models to their databases. Therefore, if you know your system or motherboard brand and model, you can find the memory that is recommended.

- Download and run analysis software that the memory module maker or a third party provides. CPU-Z and similar programs use the SPD chip on each module to determine this information.

- Consult your system documentation. I list this option last for a reason. If you have installed BIOS upgrades, you might be able to use larger and faster memory than your documentation lists as supported by your system. You should check the latest tech notes and documentation available online for your system and check the BIOS version installed in your system to determine which memory-related features it has. A BIOS upgrade might enable your system to use faster memory.

Adding the wrong modules to a system can make it as unreliable as leaving a defective module installed and trying to use the system in that condition.

**Purchasing Memory**

When purchasing memory, you need to consider certain issues. Some are related to the manufacturing and distribution of memory, whereas others depend on the type of memory you are purchasing.

**Suppliers**

Many companies sell memory, but only a few companies actually make memory. Additionally, only a few companies make memory chips, but many more companies make memory modules. Most of the companies that make the actual RAM chips also make modules containing their own chips. Other companies, however, strictly make modules; these companies purchase memory chips from several chip makers and then produce modules with these chips. Finally, some companies don’t make either the chips or the modules. Instead, they purchase modules made by other companies and relabel them.

I refer to memory modules made by the chip manufacturers as *first-party modules*, whereas those made by module (but not chip) manufacturers I call *second-party modules*. Finally, those that are simply relabeled first- or second-party modules under a different name are called *third-party modules*. I always prefer to purchase first- or second-party modules if I can because they are better documented. In essence, they have a better pedigree, and their quality is generally more assured. Not to mention that purchasing from the first or second party eliminates one or more middlemen in the distribution process as well.
First-party manufacturers (where the same company makes the chips and the modules) include Micron (www.crucial.com), Samsung, Hynix, and others. Second-party companies that make the modules (but not the chips) include Kingston, Viking, PNY, Simple Tech, Smart, and Mushkin. At the third-party level, you are not purchasing from a manufacturer but from a reseller or remarketer instead.

Most of the large manufacturers don’t sell small quantities of memory to individuals, but some have set up factory outlet stores where individuals can purchase as little as a single module. One of the largest memory manufacturers in the world, Micron, sells direct to the consumer at www.crucial.com. Because you are buying direct, the pricing at these outlets is often competitive with second- and third-party suppliers.

Considerations in Purchasing DIMMs

When you are purchasing DIMMs, here are the main things to consider:

- Do you need DDR2, DDR3, or DDR4 versions?
- Do you need ECC or non-ECC?
- Do you need standard (unbuffered) or registered versions?
- Do you need a specific voltage?
- What speed grade do you need?
- Do you need a specific CAS latency?

Currently, DIMMs come in DDR2, DDR3, and DDR4 versions. They are not interchangeable because they use completely different signaling and have different notches to prevent a mismatch. High-reliability systems such as servers can use ECC versions, although most desktop systems use the less-expensive non-ECC types. Most systems use standard unbuffered DIMMs, but file server or workstation motherboards designed to support large amounts of memory might require registered DIMMs (which also include ECC support). Registered DIMMs contain their own memory registers, enabling the module to hold more memory than a standard DIMM. DIMMs come in a variety of speeds, with the rule that you can always substitute a faster one for a slower one, but not vice versa.

Some memory modules are designed to run on non-standard voltages, which may be useful when overclocking them. Unfortunately this can also cause problems for systems where stock (nonoverclocked) memory settings are used. Standard voltages for DDR, DDR2, DDR3, and DDR4 modules are 2.5V, 1.8V, 1.5V, and 1.2V, respectively. If you buy a DDR3 module rated at a higher voltage (1.6V or higher), it might not perform reliably when run on the standard 1.5V setting. I’ve seen systems with constant lockup and crashing problems due to improperly configured memory like this. My recommendation is to purchase only memory rated to run on the standard voltage for that type, which is 1.5V in the case of DDR3 and 1.2V in the case of DDR4.

Another speed-related issue, as discussed earlier in this chapter, is the column address strobe latency. Sometimes this specification is abbreviated CAS or CL and is expressed in a number of cycles, with lower numbers indicating higher speeds (fewer cycles). The lower CAS latency shaves a cycle off a burst mode read, which marginally improves memory performance. Single data rate DIMMs are available in CL3 or CL2 versions. DDR DIMMs are available in CL2.5 or CL2 versions. DDR2 DIMMs are available in CL 3, 4, or 5. DDR3 DIMMs are available in CL 5, 6, 7, 8, and 9. DDR4 modules are available in CL 12, 14, 15, and 16. With all memory types, the lowest CL number is the fastest (and usually the most expensive) memory type. You can mix DIMMs with different CAS latency ratings, but the system usually defaults to cycling at the slower speeds of the lowest common denominator.
Considerations in Purchasing Obsolete Memory

Many people are surprised to find that obsolete memory types cost much more than those that current systems use. This is because of simple supply and demand; what is least popular generally costs the most. This can make adding memory to older systems cost prohibitive.

For example, in February 2015, a 1GB DDR PC2700 module cost about $30 at Crucial.com. A 1GB DDR2 PC2-5300 or PC2-6400 module was about $23, and a 1GB DDR3 PC3-12800 module was about $16. As you can see from this comparison, it could cost almost twice as much to buy the same amount of RAM for a system that uses the old DDR memory as current DDR3 memory (which is much faster and also available at higher capacities).

Tip

Instead of buying "new" obsolete memory for older systems, check with computer repair shops, eBay, Craigslist, websites specializing in surplus memory, or other users who might have a collection of old parts.

High-reliability systems might want or need ECC versions, which have extra ECC bits. As with other memory types, you can mix ECC and non-ECC types, but systems can’t use the ECC capability.

Replacing Modules with Higher-Capacity Versions

If all the memory module slots on your motherboard are occupied, your best option is to remove an existing bank of memory and replace it with higher-capacity modules.

However, just because higher-capacity modules are available to plug into your motherboard, don’t automatically assume the higher-capacity memory will work. Your system’s chipset, BIOS, and OS set limits on the capacity of the memory you can use. Check your system or motherboard documentation to see which size modules work with it before purchasing the new RAM. You should make sure you have the latest BIOS for your motherboard when installing new memory.

If your system supports dual- or triple-channel memory, you must use modules in matched pairs or triples (depending on which type your system supports) and install them in the correct location on the motherboard. Consult your motherboard manual for details.

Installing Memory Modules

When you install or remove memory, you are most likely to encounter the following problems:

- Electrostatic discharge
- Improperly seated modules
- Incorrect memory configuration settings in the BIOS Setup

To prevent electrostatic discharge (ESD) when you install sensitive memory chips or boards, you shouldn’t wear synthetic-fiber clothing or leather-soled shoes because these promote the generation of static charges. Remove any static charge you are carrying by touching the system chassis before you begin, or better yet, wear a good commercial grounding strap on your wrist. You can order one from any electronics parts store. A grounding strap consists of a conductive wristband grounded at the other end through a 1-meg ohm resistor by a wire clipped to the system chassis. Be sure the system you are working on is unplugged.
Caution

Be sure to use a properly designed commercial grounding strap; do not make one yourself. Commercial units have a 1-meg ohm resistor that serves as protection if you accidentally touch live power. The resistor ensures that you do not become the path of least resistance to the ground and therefore become electrocuted. An improperly designed strap can cause the power to conduct through you to the ground, possibly killing you.

Follow this procedure to install memory on a typical desktop PC:

1. Shut down the system and unplug it. As an alternative to unplugging it, you can turn off the power supply using the on/off switch on the rear of some power supplies. Wait about 10 seconds for any remaining current to drain from the motherboard.

2. Open the system. See the system or case instructions for details.

3. Connect a static guard wrist strap to your wrist and then to a metal portion of the system chassis, such as the frame. Make sure the metal plate on the inside of the wrist strap is tight against the skin of your wrist.

4. Some motherboards feature an LED that glows as long as the motherboard is receiving power. Wait until the LED dims before removing or installing memory.

5. Move obstructions inside the case, such as cables or wires, out of the way of the memory modules and empty sockets. If you must remove a cable or wire, note or take a picture of its location and orientation so you can replace it later.

6. If you need to remove an existing module, flip down the ejector tab at each end of the module and lift the module straight up out of the socket. Note the keying on the module.

7. Note the specific locations needed if you are inserting modules to operate in dual-channel mode. The sockets for dual-channel memory might use a different-colored plastic to distinguish them from other sockets, but ultimately you should consult the documentation for your motherboard or system to determine the proper orientation.

8. To insert a module into a socket, ensure that the ejector tabs are flipped down on the socket you plan to use. DIMMs are keyed by one or more notches along the bottom connector edges that are offset from the center so they can be inserted in only one direction, as shown in Figure 6.20.

9. Push down on the module until the ejector tabs lock into place in the notch on the side of the module. It’s important that you not force the module into the socket. If the module does not slip easily into the slot and then snap into place, it is probably not oriented or aligned correctly. Forcing the module could break it or the socket. Refer to Figure 6.20 for details.

10. Replace any cables or wires you disconnected.

11. Close the system, reconnect the power cable, and turn on the PC.

After installing the memory and putting the system back together, you might have to run the BIOS Setup and resave with the new amount of memory being reported. Most systems automatically detect the new amount of memory and reconfigure the BIOS Setup settings for you. Most systems today also don’t require setting any jumpers or switches on the motherboard to configure them for your new memory.

After configuring your system to work properly with the additional memory, you might want to run a memory-diagnostics program to ensure that the new memory works properly.
Troubleshooting Memory

Memory problems can be difficult to troubleshoot. For one thing, computer memory is still mysterious to people because it is a kind of “virtual” thing that can be hard to grasp. The other difficulty is that memory problems can be intermittent and often look like problems with other areas of the system, even software. This section shows simple troubleshooting steps you can perform if you suspect you are having a memory problem.

To troubleshoot memory, you first need some memory-diagnostics testing programs. You already have several and might not know it. Every motherboard BIOS has a memory diagnostic in the POST that runs when you first turn on the system. In most cases, you also receive a memory diagnostic on a utility disk that came with your system. Many commercial diagnostics programs are on the market, and almost all of them include memory tests.

When the POST runs, it not only tests memory, but it also counts it. The count is compared to the amount counted the last time BIOS Setup was run; if it is different, an error message is issued. As the POST runs, it writes a pattern of data to all the memory locations in the system and reads that pattern back to verify the memory works. If any failure is detected, you see or hear a message. Audio messages (beeping) are used for critical or “fatal” errors that occur in areas important for the system's operation. If the system can access enough memory to at least allow video to function, you see error messages instead of hearing beep codes.

See Chapter 19, “PC Diagnostics, Testing, and Maintenance,” for detailed listings of the BIOS beep and other error codes, which are specific to the type of BIOS you have.

If your system makes it through the POST with no memory error indications, there might not be a hardware memory problem, or the POST might not be able to detect the problem. Intermittent
memory errors are often not detected during the POST, and other subtle hardware defects can be hard for the POST to catch. The POST is designed to run quickly, so the testing is not nearly as thorough as it could be. That is why you often have to boot from standalone diagnostic media (normally an optical disc or a bootable flash drive) and run a true hardware diagnostic to do more extensive memory testing. You can run these types of tests continuously and leave them running for days if necessary to hunt down an elusive intermittent defect.

Fortunately, several excellent memory test programs are available for free download. Here are some I recommend:

- **Microsoft Windows Memory Diagnostic**—included with Vista and later
- **Memtest86**—www.memtest86.com
- **Ultimate Boot CD**—www.ultimatebootcd.com

Not only are these free, but they also are available in a bootable format, which means you don’t have to install software on the system you are testing. The bootable format is actually required in a way because Windows and other OSs prevent the direct access to memory and other hardware required for testing. These programs use algorithms that write different types of patterns to all the memory in the system, testing every bit to ensure it reads and writes properly. They also turn off the processor cache to ensure direct testing of the modules and not the cache. Some, such as Windows Memory Diagnostic, even indicate the module that is failing should you encounter an error. Note that a version of the Windows Memory Diagnostic is also included with Windows 7/8.1/10 and Vista. It can be found as part of the Administrative Tools (mdsched.exe), as well as on the bootable install DVDs under the Repair option.

The Ultimate Boot CD includes Memtest86 and several other memory diagnostic programs. Both the Ultimate Boot CD and the Windows Vista and later install DVDs (containing the Windows Memory Diagnostic) can also be installed on a bootable USB flash drive, which makes them much more convenient to use. To create a bootable flash drive with the Ultimate Boot CD you would use the ubcd2usb command as described in the “Customizing UBCD” page on the www.ultimatebootcd.com website. To create a bootable flash drive version of a Windows 7/8.1/10 or Vista installation DVD you can use the Windows 7 USB/DVD download tool provided by Microsoft (http://tinyurl.com/4qfdm4x). Note that although the tool has “Windows 7” in the name, it works on Windows 8.1/10 and Vista discs as well. If you want to test the memory on a system that already has Windows 7/8.1/10 or Vista installed, merely run the mdsched.exe command or open the Control Panel, Administrative Tools and select the Windows Memory Diagnostic, which enables you to restart the system and run the test immediately or set the system to run the test automatically on the next restart.

One problem with software-based memory diagnostics is that they do only pass/fail type testing; that is, all they can do is write patterns to memory and read them back. They can’t determine how close the memory is to failing—only whether it worked. For the highest level of testing, the best thing to have is a dedicated memory test machine, usually called a module tester. These devices enable you to insert a module and test it thoroughly at a variety of speeds, voltages, and timings to let you know for certain whether the memory is good or bad. Versions of these testers are available to handle all types of memory modules. I have defective modules, for example, that work in some systems (slower ones) but not others. What I mean is that the same memory test program fails the module in one machine but passes it in another. In the module tester, it is always identified as bad right down to the individual bit, and it even tells me the actual speed of the device, not just its rating. Companies that offer memory module testers include Tansys (www.tansys.com), CST (www.simmtester.com), and Innoventions (www.memorytest.com). They can be expensive, but for a high volume system builder or repair shop, using one of these module testers can save time and money in the long run.
After your OS is running, memory errors can still occur, typically identified by error messages you might receive. Here are the most common:

- **Parity errors**—The parity-checking circuitry on the motherboard has detected a change in memory since the data was originally stored. (See the “How Parity Checking Works” section earlier in this chapter.)

- **General or global protection faults**—A general-purpose error indicating that a program has been corrupted in memory, usually resulting in immediate termination of the application. This can also be caused by buggy or faulty programs.

- **Fatal exception errors**—Error codes returned by a program when an illegal instruction has been encountered, invalid data or code has been accessed, or the privilege level of an operation is invalid.

- **Divide error**—A general-purpose error indicating that a division by 0 was attempted or the result of an operation does not fit in the destination register.

If you are encountering these errors, they could be caused by defective or improperly configured memory, but they can also be caused by software bugs (especially drivers), bad power supplies, static discharges, close proximity radio transmitters, timing problems, and more.

If you suspect the problems are caused by memory, there are ways to test the memory to determine whether that is the problem. Most of this testing involves running one or more memory test programs.

Another problem with software-based diagnostics is running memory tests with the system caches enabled. This effectively invalidates memory testing because most systems have what is called a write-back cache. This means that data written to main memory is first written to the cache. Because a memory test program first writes data and then immediately reads it back, the data is read back from the cache, not the main memory. It makes the memory test program run quickly, but all you tested was the cache. The bottom line is that if you test memory with the cache enabled, you aren’t really writing to the modules, but only to the cache. Before you run any memory test programs, be sure your processor/memory caches are disabled. Many older systems have options in the BIOS Setup to turn off the caches. Current software-based memory test software such as the Windows Memory Diagnostic and Memtest86 can turn off the caches on newer systems.

The following steps enable you to effectively test and troubleshoot your system RAM. Figure 6.21 provides a boiled-down procedure to help you step through the process quickly.

First, let’s cover the memory-testing and troubleshooting procedures:

1. Power up the system and observe the POST. If the POST completes with no errors, basic memory functionality has been tested. If errors are encountered, go to the defect isolation procedures.

2. Restart the system and then enter your BIOS (or CMOS) Setup. In most systems, this is done by pressing the Del, F1, or F2 key during the POST but before the boot process begins (see your system or motherboard documentation for details). Once in BIOS Setup, verify that the memory count is equal to the amount that has been installed. If the count does not match what has been installed, go to the defect isolation procedures.

3. Find the BIOS Setup options for cache and then set all cache options to disabled if your system supports this option. Figure 6.22 shows a typical Advanced BIOS Features menu with the cache options highlighted. Save the settings and reboot to bootable media containing the memory diagnostics program.
Start up and observe POST.

If errors are encountered, go to defect isolation procedures.

See defect isolation procedures.

If count does not match, go to defect isolation procedures.

If problems are encountered, go to defect isolation procedures.

If POST completes with no errors, basic functionality has been tested.

Restart system, enter BIOS (or CMOS) Setup. Verify that memory count is equal to installed amount.

While in the BIOS, set all cache options to disabled, save settings, and boot to a DOS-formatted or self-booting system CD or floppy disk.

Use a diagnostics program to test system base and extended memory.

If no problems are encountered, memory has tested okay. Reboot, enter BIOS Setup, and re-enable.

Figure 6.21 Testing and troubleshooting memory.

Tip
Most systems do not permit you to disable cache in BIOS setup. In such cases, I recommend using Windows Memory Diagnostic and use its advanced options to disable cache before testing memory.

4. Follow the instructions that came with your diagnostic program to have it test the system base and extended memory. Most programs have a mode that enables them to loop the test—that is, to run it continuously, which is great for finding intermittent problems. If the program encounters a memory error, proceed to the defect isolation procedures.

5. If no errors are encountered in the POST or in the more comprehensive memory diagnostic, your memory has tested okay in hardware. Be sure at this point to reboot the system, enter the
BIOS Setup, and re-enable the cache. The system will run very slowly until the cache is turned back on.

Cache options to disable in BIOS

For accurate results, before testing memory the CPU Internal (L1) and External (L2 and L3) caches should be disabled in the system BIOS Setup on systems having this option.

6. If you are having memory problems yet the memory still tests okay, you might have a problem undetectable by simple pass/fail testing, or your problems could be caused by software or one of many other defects or problems in your system. You might want to bring the memory to a module tester for a more accurate analysis. Some larger PC repair shops have such a tester. I would also check the software (especially drivers, which might need updating), power supply, and system environment for problems such as static, radio transmitters, and so forth.

Memory Defect Isolation Procedures

To use these steps, I am assuming you have identified an actual memory problem that the POST or disk-based memory diagnostics have reported. If this is the case, see the following steps and Figure 6.23 for instructions to identify or isolate which module is causing the problem.

1. Restart the system and enter the BIOS Setup. Under a menu usually called Advanced or Chipset Setup might be memory timing parameters. Select BIOS or Setup defaults, which are usually the slowest settings. If the memory timings have been manually set, as shown in Figure 6.21, reset the memory configuration to By SPD.

2. Save the settings, reboot, and retest using the testing and troubleshooting procedures listed earlier. If the problem has been solved, improper BIOS settings were the problem. If the problem remains, you likely do have defective memory, so continue to the next step.
3. Open the system for physical access to the modules on the motherboard. Identify the bank arrangement in the system. Using the manual or the legend silk-screened on the motherboard, identify which modules correspond to which banks. Remember that if you are testing a multi-channel system, you must be sure you remove all the modules in the same channel.

4. Remove all the memory except the first bank, and then retest using the troubleshooting and testing procedures listed earlier (see Figure 6.24). If the problem remains with all but the first bank removed, the problem has been isolated to the first bank, which you must replace.

5. Replace the memory in the first bank (preferably with known good spare modules, but you can also swap in others that you have removed) and then retest. If the problem still remains after
testing all the memory banks (and finding them all to be working properly), it is likely the motherboard is bad (probably one of the memory sockets). Replace the motherboard and retest.

6. At this point, the first (or previous) bank has tested to be good, so the problem must be in the remaining modules that have been temporarily removed. Install the next bank of memory and retest. If the problem resurfaces now, the memory in that bank is defective. Continue testing each bank until you find the defective module.

7. Repeat the preceding step until all remaining banks of memory are installed and have been tested. If the problem has not resurfaced after you have removed and reinstalled all the memory, the problem was likely intermittent or caused by poor conduction on the memory contacts. Often simply removing and replacing memory can resolve problems because of the self-cleaning action between the module and the socket during removal and reinstallation.

The System Logical Memory Layout

The original PC had a total of 1MB of addressable memory, and the top 384KB of that was reserved for use by the system. Placing this reserved space at the top (between 640KB and 1,024KB, instead of at the bottom, between 0KB and 640KB) led to what is often called the conventional memory barrier. The constant pressures on system and peripheral manufacturers to maintain compatibility by never breaking from the original memory scheme of the first PC has resulted in a system memory structure that is (to put it kindly) a mess. More than three decades after the first PC was introduced, even the newest systems are limited in many important ways by the memory map of the first PCs.
Chapter 6
Memory

The original PC used an Intel 8088 processor that could run only 16-bit instructions or code, which ran in what was called the real mode of the processor. These early processors had only enough address lines to access up to 1MB of memory, and the last 384KB of that was reserved for use by the video card as video RAM, other adapters (for on-card ROM BIOS or RAM buffers), and finally the motherboard ROM BIOS.

The 286 processor brought more address lines, enough to allow up to 16MB of RAM to be used, and a new mode called protected mode that you had to be in to use. One area of confusion was that RAM was now noncontiguous; that is, the OS could use the first 640KB and the last 15MB, but not the 384KB of system reserved area that sat in between.

When Intel released the first 32-bit processor in 1985 (the 386DX), the memory architecture of the system changed dramatically. There were now enough address lines for the processor to use 4GB of memory, but this was accessible only in 32-bit protected mode, in which only 32-bit instructions or code could run. Unfortunately, it took 10 years for the industry to transition from 16-bit to 32-bit OSs and applications. From a software instruction perspective, all the 32-bit processors since the 386 are really just faster versions of the same.

When AMD released the first x86-64 processor in 2003 (Intel followed suit in 2004), the 64-bit era was born. In addition to 16-bit and 32-bit modes, these chips have a 64-bit mode (commonly referred to as x64 or x86-64). 64-bit processors have three distinctly different modes, with unique memory architectures in each. For backward compatibility, 64-bit processors can run in 64-bit, 32-bit, or 16-bit modes, and 32-bit processors can run in 32-bit or 16-bit modes, each with different memory limitations. For example, a 64-bit processor running in 32-bit mode can only address 4GB of RAM, and a 64-bit or 32-bit processor running in 16-bit mode can only address 1MB of RAM. All Intel-compatible PC processors begin operation in 16-bit real mode when they are powered on. When a 32-bit or 64-bit OS loads, it is that OS code that instructs the processor to switch into 32-bit or 64-bit protected mode.

When a 32-bit OS such as Windows is loaded, the processor is switched into 32-bit protected mode early in the loading sequence. Then, 32-bit drivers for all the hardware can be loaded, and the rest of the OS can load. In 32-bit protected mode, the OSs and applications can access all the memory in the system up to 4GB. Similarly, on a 64-bit OS, the system switches into 64-bit protected mode early in the boot process and loads 64-bit drivers, followed by the remainder of the OS.

The 32-bit editions of Windows support 4GB of physical memory (RAM). What many don’t realize is that the PC system hardware uses some or all of the fourth gigabyte for the BIOS, motherboard resources, memory mapped I/O, PCI configuration space, device memory (graphics aperture), VGA memory, and so on. This means that if you install 4GB (or more) RAM, none of it past 4GB will be seen at all, and most or all of the fourth gigabyte (that is, the RAM between 3GB and 4GB) will be disabled because it is already occupied by other system hardware. This is called the 3GB limit, which is analogous to the 640K memory limit we had on 16-bit systems in the 1980s. The 16-bit addressing supported 1MB, but the upper 384K was already in use by the system hardware (BIOS, video, adapter ROM, and so on).

Figure 6.25 shows the memory map for a system using an Intel G45 chipset, which supports a maximum of 16GB of RAM. For a 32-bit OS, the line labeled “Top of usable DRAM (32-bit OS)” is at 4,096MB. Note that the PCI memory range, FLASH, APIC (Advanced Programmable Interrupt Controller), and Reserved areas take up a total of 770MB of the memory below 4GB. You can also see the 384K (0.375MB) of memory below 1MB that is used by the system. This means that if you are running a 32-bit OS, even if you have 4GB of RAM installed, the amount usable by the OS would be 4,096MB – 770MB – 0.375MB, which is 3,325.625MB (or about 3.24GB, rounded down).
Can any of that unused memory between 3GB and 4GB be reclaimed? For those running a 32-bit OS, the answer is no. However, if you are running a 64-bit OS on a system that supports memory remapping (primarily a function of the motherboard chipset and BIOS), the answer is yes. Most modern motherboard chipsets have a feature that can remap the otherwise disabled RAM in the fourth gigabyte to the fifth (or higher) gigabyte, where it will be both visible to and usable by a 64-bit OS. Note, however, that if the motherboard doesn’t support remapping, even when a 64-bit OS is being run, the memory will be lost.

FIGURE 6.25 Memory map for a system using an Intel G45 chipset.

Note that the 3GB limit is not as strictly defined as it was with the 640K limit. This means that if you do install 4GB, you might get to use as much as 3.5GB of it, or possibly as little as 2.5GB or less. It depends largely on the types of buses in the system as well as the type and number of video cards installed. With a single low-end video card, you may have access to 3.5GB. However, on a newer system with two or more PCIe x16 slots, and especially with two or more high-end PCI Express video cards installed, you may drop the usable limit to something close to 2GB.
When running 32-bit editions of Windows, I used to recommend installing a maximum of 3GB RAM, because most if not all of the fourth GB is unusable. However, on systems that support dual-channel memory, it is usually cheaper to install two 2GB modules to get 4GB than it is to install two 1GB modules and two 512MB to get 3GB. On desktop systems that support dual-channel memory, you would not want to install three 1GB modules because in that case not all the memory would run in dual-channel mode.
Index

Symbols

1/2-Baby motherboards, 170
2/3-Baby motherboards, 170
0.85” drive, 503
1” drives, 503
1-Core Ratio Limit setting (BIOS Performance menu), 333
1.8” drives, 503
2.1 GB barrier (CHS), 459
2.1 speaker configuration, 755
2.2 TB barrier, 470-471
2.5” ATA drive cables, 1067
2.5” drives, 502-503
3 GB limit, 406
3 TB drives, 1098
3D gaming audio standards, 738-740
3D graphics accelerators, 696-697
animation, 700
anti-aliasing, 700
APIs (application programming interfaces)
AMD Mantle, 703-704
DirectX, 702-703
OpenGL, 700-701
depth cueing, 699
dual-GPU scene rendering
AMD CrossFire, 705-707
AMD Eyefinity, 706
NVIDIA SLI, 704-705
PCIe lanes, 706-707
video RAM size, 707
flat shading, 697
Gouraud shading, 697
history of, 698
image abstractions, 699
image rendering, 699-700
MIP mapping, 699
perspective correction, 699
primitives, 699
scan conversion, 699
shading, 699
software optimization, 700
texture mapping, 697-699
vertices, 699
visible surface determination, 700
3D Soundback, 739
3DNow!, 69
3G mobile broadband, 840
3x series chipsets (Intel), 218-220
+3.3V power sources, 904
3.5" drive enclosure, 1068
3.5" half-height drives, 502
4-pin +12V power connectors, 941-942
4-pin to 8-pin +12V power connectors, 944
4.1 speaker configuration, 755
4.2 GB barrier (CHS), 460-462
4K mobile broadband, 840-841
4-pin +12V power connectors, 941-942
4-pin to 8-pin +12V power connectors, 944
4-pin +12V power connectors (ATX), 942-943
4.1 Surround sound, 755
5-pin DIN keyboard connectors, 808
5.1 Surround sound, 755
5.25" drives, 502
5x series chipsets (Intel), 220-224
-5V power sources, 905-906
+5V power sources, 904
6-pin auxiliary power connectors, 935-936
6-pin mini-DIN keyboard connectors, 808
6 TB UltraStar He6 (HGST), 497
6.1 Surround sound, 755
6x series chipsets (Intel), 224-225
7-Zip, 299
7.1 Surround sound, 755
7x series chipsets (Intel), 225-227
8-bit (bidirectional) parallel ports, 791-792
8-bit ISA (Industry Standard Architecture) buses, 272
8-bit processors, 96-97
8-pin +12V power connectors (ATX), 942-943
8 TB Archive v2 HDD (Seagate), 497
8.4 GB barrier, 465-466
886C connectors, 871
8x series chipsets (Intel), 227-229
9-pin serial port connectors, 787
9-pin-to-25-pin serial port connectors, 788
9x series chipsets (Intel), 229-231
10BASE-T, 861
100BASE-TX, 861
101-key keyboards, 795-796
103-key keyboards, 796-798
137 GB barrier, 466-468
168-pin SDRAM DIMMs, 378
184-pin DDR DIMMs, 378, 384
240-pin DDR2 DIMMs, 378, 384
286 processors, 97
305 RAMAC (Random Access Method of Accounting and Control), 475
386 processors, 98-99, 201-202
480x chipsets (AMD), 236
486 processors, 99
82350 chipsets, 201
Intel chipsets, 201-202
sockets, 80-83
500 series chipsets (AMD), 236
504 MiB barrier (CHS), 457
512-byte sector in recent drives, 510
528 MB barrier (CHS), 455-457
555.2 Harmonics standard (IEC), 959
586 processors. See Pentium
686 processors. See 80686 processors
690 series chipsets (AMD), 236
700 series chipsets (AMD), 237-238
726 Tape Unit, 475
800 series chipsets (AMD), 237-238
802.11a, 864-865
802.11ac, 867
802.11ad, 868
802.11b, 863-864
802.11g, 865
802.11n, 865-867
900 series chipsets (AMD), 237-241
915 family chipsets (Intel), 215
925X family chipsets (Intel), 215-216
945 Express family chipsets (Intel), 216
955X chipsets (Intel), 217
975X chipsets (Intel), 217
1000-2 Harmonics, 959
1000-3 Flicker, 959
Adaptive Contrast Management (ACM), 715

1080i HDTV, 715
1394 setting (BIOS Onboard Devices menu), 316
1394 standards (IEEE), 776-778
1394a, 776-777
1394b, 777-778
1394b S3200, 778
4004 processors, 34
6502 processors, 36
8000 (8151) chipsets (AMD), 234-235
8008 processors, 35
8085 processors, 35
8086 mode, 50
8086 processors, 36, 95-96
8088 processors, 36, 96-97
9100A electronic calculator (Hewlett-Packard), 22
4004 processors, 34
80286 processors, 97
80386 processors, 98-99, 201-202
80486 processors, 80-83, 99
82350 chipsets, 201
80586 processors. See Pentium
80686 processors
Celeron, 107-108
Pentium-compatible, 69
Pentium II, 69-70, 103-106
Pentium III, 106-107
Pentium Pro, 69-70, 103-104
82350 chipsets (Intel), 201

A

A series chipsets (AMD), 241-243
ABC (Atanasoff-Berry Computer), 5, 10
absolute time in pre-groove (ATIP), 585
AC '97 integrated audio, 749
AC power switches
front panel, 927-928
integral, 927
AC ripple, 958
ACC (Advanced Clock Calibration), 148
Accelerated Graphics Port (AGP), 270, 678-679
accelerated hub architecture (AHA), 199
access points, 887, 892, 899
access times
CD drives, 645
DVD drives, 645
HDDs (hard disk drives), 542
acclimation to temperatures (HDDs), 534
ACM (Adaptive Contrast Management), 715
ACPI (Advanced Configuration and Power Interface), 347-348, 966-968
ACPI suspend mode, 970
Acronis True Image, 546
active heatsinks, 153-155
active low signals, 925
active PFC (power factor correction), 959
active preventative maintenance, 1075-1076
cleaning, 1077
chemical-freeze sprays, 1078
compressed air, 1078
contact cleaners/lubricants, 1078
contacts, 1080
keyboards, 1080-1081
mouse devices, 1080-1081
swabs, 1079
system disassembly, 1079-1080
vacuum cleaners, 1079
weekly and monthly checklists, 1076-1077
Active Processor Cores setting (BIOS main menu), 313
active-matrix LCD (liquid crystal display) monitors, 717-718
actuator mechanisms, 504
servo mechanisms, 528-531
dedicated servo, 531-532
disk sweep, 529
embedded servo, 530-531
grey code, 528
servowriters, 528
thermal recalibration, 529
wedge servo, 530
stepper motors, 526
voice-coil actuators, 526-528
ad hoc mode, 887
Adalin, 738
adapters. See also 3D graphics accelerators; ATA (AT Attachment); SCSI (small computer system interface)
2.5” ATA drive cables and adapters, 1067
audio adapters, 504, 736, 1005
data transfer adapters, 1067
expansion cards, 1033
integrated adapters, 1002
NICs (network interface cards), 869-870, 1053
bus types, 870
connectors, 870-871
full-duplex, 870
half-duplex, 870
installation, 898
speed, 870
testing, 899
wireless NICs, 887-888
PCI (Peripheral Connect Interface) buses, 266
troubleshooting, 1089-1090, 1100
USB/FireWire cable adapter, 1068
video adapters, 658, 722
chips, 673
choosing, 1004-1005
components, 671-672
DAC (digital-to-analog converter), 678
heterogeneous adapters, 723
homogeneous adapters, 723
installation, 1031
integrated video/ motherboard chipsets, 659-663
processors with integrated video, 663-670
removing, 1033
testing, 726-727
troubleshooting, 725-726
types of, 658-659
UMA (unified memory architecture), 659
video BIOS, 672
video drivers, 727
video RAM, 674-678, 707
Adaptive Contrast Management (ACM), 715
Adaptive Differential Pulse Code Modulation (ADPCM), 746
ADCs (analog-to-digital converters), 735
address buses, 48-49
Address Mark sector field, 508
address storing (switches), 884
addresses
CMOS RAM addresses, 303-304
MAC addresses, 869
port addresses, 276-277
addressing sectors
CHS (cylinder head sector) 2.1 GB barrier, 459
4.2 GB barrier, 460-462
8.4 GB barrier, 465-466
528 MB barrier, 455-457
BIOS commands versus
ATA commands, 454
CHS bit-shift translation, 457-459
CHS/LBA conversions, 453-454
LBA (logical block address)
137 GB barrier and beyond, 466-468
BIOS commands versus
ATA commands, 454
CHS/LBA conversions, 453-454
compared to CHS (cylinder
head sector), 452-453
LBA-assist translation, 462-464
prefixes for decimal/binary
multiples, 451
AdLib sound card, 736
ADPCM (Adaptive Differential Pulse Code Modulation), 746
ADSL (Asymmetric DSL), 838
Advanced Clock Calibration
(ACC), 148
Advanced Configuration and
Power Interface (ACPI), 347-348, 966-968
Advanced Flat Panel Display
menu (BIOS Setup), 325-326
Advanced Format (4K sectors), 511-513
Advanced Host Controller Interface (AHCI), 444-445
advanced Linux sound
architecture (ALSA), 748
Advanced menus (BIOS Setup), 344
Advanced Optical Disc
(AOD), 616
Advanced Power Management
(APM), 347, 965
advanced processing units
(APUs), 137-139
Advanced Programmable
Interrupt Controller
(APIC), 275
Advanced RLI (ARLL), 488
advanced vector extensions
(AVX), 68-69
Advanced Video Coding High
Definition (AVCHD), 552
AFC (antiferromagnetically
coupled) media, 523-524
After Power Failure setting
(BIOS Power menu), 337
AGC (Automatic Gain Control), 601, 742
AGP (Accelerated Graphics
Port), 270, 678-679
AHA (accelerated hub
architecture), 199
AHCI (Advanced Host
Controller Interface), 444-445
air bearing heads, 507
air filters, 532-533
Alderwood (925X) chips sets, 215-216
algorithms, ADPCM (Adaptive
Differential Pulse Code
Modulation), 746
Ali Corporation. See ULi Electronics chips sets
A-Link architecture, 201
All-in-One Chassis setting
(BIOS Video menu), 324
All-On Temperature setting
(BIOS Fan Control &
Real-Time Monitoring
menu), 327
Allied Electronics, 1064
allocation units, 519
Allow Simultaneous PCIe x16
Video Card (PEG) and IGD
setting (BIOS Performance
menu), 330
alpha particles, 389
ALSA (advanced Linux sound
architecture), 748
Altair, 15, 22
aluminum
aluminum foil, 1010
aluminum/magnesium alloy
platters, 522
in hard disks, 477
Amazon Cloud Drive, 566
AMD
AMD-specific BIOS settings, 346
AMD-V, 73
chipsets, 232
AMD 690 series chipsets, 234-235
AMD 700 series chipsets, 237-238
AMD 800 series chipsets, 237-238
AMD 900 series chipsets, 237-241
AMD 8000 (8151), 234-235
AMD A series chipsets, 241-243
AMD (ATI) 480x and 500
series chipsets, 236
reference table, 233
CrossFire, 705-707
eyefinity, 706
Fusion/HSA (Heterogeneous Systems Architecture) APUs, 137-139
integrated graphics architecture, 197
integrated video, 667-670
Mantle, 703-704
processors
Athlon, 122-123
Athlon 64, 124-128
Athlon 64 FX, 124-130
Athlon 64 X2, 128-130
Athlon MP, 124
Athlon X2, 128-130
Athlon XP, 124
Bulldozer FX, 134-137
code names, 95
development of, 37-39
ATA (AT Attachment)

Index

ATA/ATAPI-4 standard, 416-417
ATA/ATAPI-5 standard, 417
ATA/ATAPI-6 standard, 417-418
ATA/ATAPI-7 standard, 418-419
ATA/ATAPI-8 standard, 419
ATAPI (AT Attachment Packet Interface), 449
ATA Security Mode, 447-448
busmaster ATA, 429
CAM ATA (Common Access Method ATA), 411
capacity limitations, 450-451
2.1 GB barrier, 459
2.2 TB barrier, 470-471
4.2 GB barrier, 460-462
8.4 GB barrier, 465-466
137 GB barrier and beyond, 466-468
BIOS limitations, 451-452
BIOS versus ATA commands, 446-447
connectors, 417
drive capacity limitations, 450-451
1.2 GB barrier, 459
2.2 TB barrier, 470-471
4.2 GB barrier, 460-462
8.4 GB barrier, 465-466
137 GB barrier and beyond, 466-468
BIOS limitations, 451-452
BIOS versus ATA commands, 454
CHS (cylinder head sector) addressing, 455-457
commands, 446-447
table of, 450
drive capacity limitations, 450-451
endecs, 410
explained, 409
GPT (GUID Partition Table), 470-471
history of, 410-412
HPAs (host protected areas), 448-449
operating system limitations, 468-469
PATA (Parallel ATA), 412, 426-429
DMA (direct memory access) transfer modes, 429-430
I/O cables, 423-425

DirectX, 702-703
OpenGL, 700-701
APM (Advanced Power Management), 347, 965
App Shop (ASRock), 296
Apple
Apple I, 16
Apple II, 16
Mac OS X, 25-26
proprietary design, 18
shift to PC-based architecture, 18-19
application programming interfaces. See APIs (application programming interfaces)
APUs (advanced processing units), 137-139
Arc Touch Mouse (Microsoft), 820
architecture, layered, 283-284
areal density, 492-494
ARLL (Advanced RLL), 488
ARPAnet, 6
ASCR (ASUS Smart Contrast Ratio), 715
a-Si (hydrogenated amorphous silicon), 718
ASIO4ALL project, 748
aspect ratio, 709-710
ASRock App Shop, 296
assembly. See system assembly
ASUS
Ai Charger app, 768
ASCR (ASUS Smart Contrast Ratio), 715
Disk Unlocker, 309
EZ Update, 296
USB BIOS Flashback, 298
Asymmetric DSL (ADSL), 838
asynchronous, 784
AT motherboards
Baby-AT, 169-170
full-size AT, 167-168
power supply connectors, 929-931
AT power supply connectors, 929-931
ATA (AT Attachment)
ATA-1 standard, 414
ATA-2 standard, 415
ATA-3 standard, 415
ATA/ATAPI-4 standard, 416-417
ATA/ATAPI-5 standard, 417
ATA/ATAPI-6 standard, 417-418
ATA/ATAPI-7 standard, 418-419
ATA/ATAPI-8 standard, 419
ATAPI (AT Attachment Packet Interface), 449
ATA Security Mode, 447-448
busmaster ATA, 429
CAM ATA (Common Access Method ATA), 411
capacity limitations, 537
CHS (cylinder head sector) addressing, 455-457
commands, 446-447
connectors, 417
drive capacity limitations, 450-451
2.1 GB barrier, 459
2.2 TB barrier, 470-471
4.2 GB barrier, 460-462
8.4 GB barrier, 465-466
137 GB barrier and beyond, 466-468
BIOS limitations, 451-452
BIOS versus ATA commands, 454
CHS bit-shift translation, 457-459
CHS/LBA conversions, 453
CHS limitations, 455-457
CHS versus LBA, 452-453
LBA-assist translation, 462-464
table of, 450
endecs, 410
explained, 409
GPT (GUID Partition Table), 470-471
history of, 410-412
HPAs (host protected areas), 448-449
operating system limitations, 468-469
PATA (Parallel ATA), 412, 426-429
DMA (direct memory access) transfer modes, 429-430
I/O cables, 423-425

Duron, 123
Excavator, 137
K5, 102-103
K6, 69, 122
K6-2, 122
K6-3, 122
K10, 130-134
Piledriver FX, 134-137
Sempron, 128
specifications, 45-47
streamer processors, 137
AMD Turbo CORE setting (BIOS Setup), 346
AMD-V, 73
American Power Conversion (APC), 988
AMI (American Megatrends, Inc.), 291
BIOS error messages, 351
POST error codes, 1042-1043
AMIDiag Suite, 1055
amorphous state, 589
amplification, 753
amplitude, 734
AMR (anisotropic magneto-resistant) heads, 481-482
AMR (Audio Modem Riser), 256
analog RCA sound card connectors, 743
analog-to-digital converters (ADCs), 735
Andromeda Research Labs, 289
animation, 700
anisotropic magneto-resistant (AMR) heads, 481-482
antennas, 888
antialiasing, 700
antiferromagnetically coupled (AFC) media, 523-524
AOD (Advanced Optical Disc), 616
APC (American Power Conversion), 988
aperture, numerical, 615
APIC (Advanced Programmable Interrupt Controller), 275
a-pinene, 1078
APIs (application programming interfaces)
AMD Mantle, 703-704
defined, 283

AOD (Advanced Optical Disc), 616
APC (American Power Conversion), 988
aperture, numerical, 615
APIC (Advanced Programmable Interrupt Controller), 275
a-pinene, 1078
APIs (application programming interfaces)
AMD Mantle, 703-704
defined, 283

Duron, 123
Excavator, 137
K5, 102-103
K6, 69, 122
K6-2, 122
K6-3, 122
K10, 130-134
Piledriver FX, 134-137
Sempron, 128
specifications, 45-47
streamer processors, 137
AMD Turbo CORE setting (BIOS Setup), 346
AMD-V, 73
American Power Conversion (APC), 988
AMI (American Megatrends, Inc.), 291
BIOS error messages, 351
POST error codes, 1042-1043
AMIDiag Suite, 1055
amorphous state, 589
amplification, 753
amplitude, 734
AMR (anisotropic magneto-resistant) heads, 481-482
AMR (Audio Modem Riser), 256
analog RCA sound card connectors, 743
analog-to-digital converters (ADCs), 735
Andromeda Research Labs, 289
animation, 700
anisotropic magneto-resistant (AMR) heads, 481-482
antennas, 888
antialiasing, 700
antiferromagnetically coupled (AFC) media, 523-524
AOD (Advanced Optical Disc), 616
APC (American Power Conversion), 988
aperture, numerical, 615
APIC (Advanced Programmable Interrupt Controller), 275
a-pinene, 1078
APIs (application programming interfaces)
AMD Mantle, 703-704
defined, 283

Duron, 123
Excavator, 137
K5, 102-103
K6, 69, 122
K6-2, 122
K6-3, 122
K10, 130-134
Piledriver FX, 134-137
Sempron, 128
specifications, 45-47
streamer processors, 137
AMD Turbo CORE setting (BIOS Setup), 346
AMD-V, 73
American Power Conversion (APC), 988
AMI (American Megatrends, Inc.), 291
BIOS error messages, 351
POST error codes, 1042-1043
AMIDiag Suite, 1055
amorphous state, 589
amplification, 753
amplitude, 734
AMR (anisotropic magneto-resistant) heads, 481-482
AMR (Audio Modem Riser), 256
analog RCA sound card connectors, 743
analog-to-digital converters (ADCs), 735
Andromeda Research Labs, 289
animation, 700
anisotropic magneto-resistant (AMR) heads, 481-482
antennas, 888
antialiasing, 700
antiferromagnetically coupled (AFC) media, 523-524
AOD (Advanced Optical Disc), 616
APC (American Power Conversion), 988
aperture, numerical, 615
APIC (Advanced Programmable Interrupt Controller), 275
a-pinene, 1078
APIs (application programming interfaces)
AMD Mantle, 703-704
defined, 283
ATA (AT Attachment)

ATX12V 2.x 24-pin power supply connectors, 936-939
ATX12V power supply, 910-913
ATX/ATX12V 1.x power supply connectors
6-pin auxiliary power connectors, 935-936
20-pin main power connectors, 931-933
maximum power-handling capabilities, 934-935
Molex Mini-Fit Jr. power connectors, 933-934

Audio, 736, 748

Amplitude, 734
Audio menu (BIOS Setup), 320
CDs. See CDs explained, 733-734
Frequency response, 734
Front panel audio connector pinout, 252-253
Headphones, 754
Integrated audio chipsets, 748-749
Microphones, 755-756
Microsoft Windows audio support, 736
3D gaming standards, 738-739
core audio APIs, 737-738
DirectX, 737
Legacy audio support, 740
Optimizing system for, 996
Pitch, 734
POST beep codes, 1041
AMI BIOS, 1042-1043
Award BIOS/Phoenix FirstBIOS, 1043-1044
IBM BIOS, 1048
IBM/Lenovo, 1052-1053
Phoenix BIOS 4 and later, 1048
Phoenix BIOS 486 and earlier, 1046-1047
Sampling, 578, 735-736
SNR (signal-to-noise ratio), 735
Sound cards, 736, 743
Choosing, 1005
Connectors, 740-744
Data compression, 746-747
Drivers, 747

Audacity, 736, 748
beep error codes (POST)  1107

Index

history of, 736
integrated audio chipsets, 748
MIDI support features, 745-746
monophonic/stereophonic, 745
signal processing methods, 743
Sound Blaster, 736
Sound Blaster Pro, 736
sound production features, 748
troubleshooting, 749
USB-based audio processors, 745
volume control, 745

speakers
amplification, 753
DBB (dynamic bass boost), 754
explained, 753
frequency response, 753
interference, 754
satellite speakers, 754
sleep feature, 754
surround sound, 754-755
total harmonic distortion, 756
volume control, 754
watts, 753
total harmonic distortion, 734
troubleshooting, 1092
advanced features, 752
with Device Manager, 752
low volume, 750
no sound, 750
problems playing specific file formats, 751
scratchy sound, 751-752
speakers, 751
startup problems, 752

audio data information
CDs, 577-578
DVDs, 598-599
audio endpoint devices, 737
Audio Interface Wizard, 748
Audio menu (BIOS Setup), 320
Audio Modem Riser (AMR), 256
Audio setting (BIOS Onboard Devices menu), 316
AUI (attachment unit interface), 871
auto-sensing, 741
AUTOEXEC.BAT file, 1061
automated bootable media images, upgrading flash ROM from, 298
automatic drive detection, 1030-1031
Automatic Gain Control (AGC), 601, 742
automatic head parking, 532
aux in sound card connectors, 743
auxiliary power connectors (ATX), 935-936
AVCHD (Advanced Video Coding High Definition), 552
average access times (HDDs), 542
average Seek times, 541
AVX (advanced vector extensions), 68-69
Award BIOS error messages, 351
POST error codes, 1043-1044
POST onscreen messages, 1044-1045
Azalia HD Audio, 749
azimuth, 527

Babbage, Charles, 5
Baby-AT motherboards, 169-170
Back Panel 61XX eSATA (Gen 2) setting (BIOS SATA Drives menu), 320
back probing, 976
backing plates, 153
Backlight-Off to Power-Down Delay setting (BIOS Advanced Flat Panel Display menu), 325
backup power supply
standby power supply, 985-986
UPS (uninterruptible power supply), 986-988
backups
CMOS RAM, 294
ROM BIOS, 293-294
backward compatibility
DVD drives, 627
motherboard power connectors, 944-946
SATA (Serial ATA), 431
Backward Compatibility Mode setting (BIOS USB menu), 318
bad pixels (LCDs), 730
BadUSB, 775
Balanced Technology Extended (BTX) motherboards, 174-177
ball-driven mice, 815
bandwidth, 48
buses, 257-261
cable bandwidth, 835
banks (memory), 382, 387-388
BAPCo SYSmark, 55
Bardeen, John, 6, 12
base memory, 315
basic input/output system.
See BIOS (basic input/output system)
batteries
connectors, 253
lithium coin cell batteries, 1068
replacing, 992
RTC/NVRAM, 988
modern CMOS batteries, 989-990
obsolete/unique CMOS batteries, 990-991
troubleshooting, 991-992
BBUL (bumpless build-up layer), 80
BD (Blu-ray discs), 31, 653
BD-R, 614
BD-RE, 614
BD-RE XL, 614
BD-ROM, 614
compared to DVD, 615
drive speed, 644
explained, 613
movie playback on PCs, 628
region codes, 640
speed and read/write times, 614-615
BDF (Blu-ray Disc Founders), 613
bearings, fluid dynamic, 535
Bearlake (3x series) chipsets, 218-220
BEDO (burst EDO), 367
beep error codes (POST), 1041
AMI BIOS, 1042-1043
Award BIOS/Phoenix FirstBIOS, 1043-1044
IBM BIOS, 1048
bench testing power supplies
digital infrared thermometers, 979
power supply testers, 977-978
variable voltage transformers, 979-980
benchmarks, processor, 54-55
Berg power connectors, 947-948
Berkeley, Edmund C., 22
Berners-Lee, Tim, 8
Berry, Clifford, 10
bidirectional (8-bit) parallel ports, 791-792
The Big Haswell PSU Compatibility List, 120
binary digits. See bits
binary multiples, prefixes for, 451
biometric security, 559
BIOS (basic input/output system)
ATA drive capacity limitations, 451-452
backing up, 293-294
boot ROM, 292
bootstrap loader, 285
capacity limitations, 537-538
choosing, 1001
CMOS RAM addresses, 303-304
backing up, 294
configuring. See Setup (BIOS)
declared, 284-285
diagnostic status byte codes, 304
defined, 24, 281
error messages
AMI BIOS, 351
Award BIOS, 351
Compaq BIOS, 351
explained, 348-349
IBM BIOS, 350-351
Insyde BIOS, 352
MBR boot errors, 352-353
Phoenix BIOS, 352
explained, 281-284, 1000
guides, 282
flash ROM, upgrading, 295-296
ASUS USB BIOS Flashback, 298
automated bootable media images, 298
BIOS Setup executable upgrades, 297-298
eergency flash ROM recovery, 300-302
safety, 300
user-created bootable media, 299-300
Windows executable upgrades, 296
write protection, 295
hardware/software, 292
IPL (initial program load) ROM, 292
manufacturers, 291
motherboard ROM BIOS, 285-287
EEPROM (electronically erasable programmable ROM), 290-291
EPROM (erasable programmable ROM), 289-290
flash ROM, 290-291
mask ROM, 288
ROM (programmable ROM), 288-289
ROM hardware, 285-286
ROM shadowing, 287
non-PC ROM upgrades, 290
paragraphs, 286
PnP (Plug and Play), 347
ACPI (Advanced Configuration and Power Interface), 347-348
device IDs, 347
POST. See POST (power on self test)
preboot environment, 305-307
RTC/NVRAM (real-time clock/nonvolatile memory) chips, 284
SATA (Serial ATA) configuration, 443
Settings Glossary, 315, 337
Setup
accessing, 310
Advanced Flat Panel Display menu, 325-326
AMD-specific BIOS settings, 346
Audio menu, 320
Boot menu, 341-343
Boot—Boot Display Options menu, 343-344
Boot—Secure Boot Configuration menu, 345
Exit menu, 345-346
Fan Control & Real-Time Monitoring menu, 327-328
main menu, 313-315
Maintenance menu, 311-312
Onboard Devices menu, 315-317
overview, 285, 344, 310-311
PCI/PClle Add-in Slots menu, 319
Performance menu, 328-330
Performance—Bus
Overrides menu, 330
Performance—Memory
Overrides menu, 331-332
Performance—Processor
Overrides menu, 332-334
Power menu, 337-340
running, 1033-1035
SATA Drives menu, 320-323
Security menu, 334-337
USB menu, 317-319
Video menu, 323-325
UEFI (Unified Extensible Firmware Interface)
BIOS limitations, 307-309
support for, 309
upgrading
advantages, 292
BIOS versions, 293
CMOS RAM addresses, 303-304
CMOS RAM backups, 294
CMOS RAM diagnostic status byte codes, 304
flash ROM, 295-302
Index

keyboard controller chips, 295
obtaining updates, 293
versions, 293
@BIOS utility, 296
BIOS RAM checksum error—System halted (error message), 1044
BIOS Setup Auto-Entry setting (BIOS Boot menu), 341
BIOS Version setting (BIOS main menu), 313
BIOSAgentPlus, 141
bit-shift translation (CHS), 457-459
bitsetting, 612
bits (binary digits), 11
bit cells, 478
bit-level ECC (error correction codes), 472
merge bits, 582
black power switch connector wires, 927
Blacklisted Signature Database (dbx) setting (BIOS Secure Boot Configuration menu), 345
blanks, 143
BLER (block error rate), 580
Blinkenlights Archaeological Institute, 22
block error rate (BLER), 580
blocked data with distributed parity, 472
blocked data with double distributed parity, 472
Blue Book standard (CD EXTRA), 623
blue power switch connector wires, 927
Blue Ripple Sound, 738
Blue Screen Of Death (BSOD) errors, 1053
Bluetooth, 828, 868-869, 889
Bluetooth Wireless setting (BIOS Onboard Devices menu), 316
Blu-ray, See BD (Blu-ray Discs)
Blu-ray Disc Founders (BDF), 613
bonding, 77
Boot—Secure Boot Configuration menu (BIOS Setup), 345
Boot Configuration menu (BIOS Setup), 344
Boot Device Priority setting (BIOS Boot menu), 341
Boot Drive Order setting (BIOS Boot menu), 341
Boot menu (BIOS Setup), 341-343
Boot Menu Type setting (BIOS Boot menu), 341
Boot Network Devices Last setting (BIOS Boot menu), 341
boot process. See also POST (power on self test)
BIOS boot error messages
AMI BIOS messages, 351
Award BIOS messages, 351
Compaq BIOS messages, 351
explained, 349
IBM BIOS messages, 350-351
Insyde BIOS messages, 352
Phoenix BIOS messages, 352
BIOS Setup, 341-345
bootable CDs, 649, 652
booting from CD-ROM, 1058
quiet boots, 293
troubleshooting, 1089, 1096
Windows 8, 1063
Windows 8.1/10, 1063
Windows 9x/Me, 1061
Windows 2000/XP, 1061-1062
Windows Vista/7, 1062-1063
boot ROM (read-only memory), 292
Boot to Network setting (BIOS Boot menu), 341
Boot to Optical Devices setting (BIOS Boot menu), 341
Boot to Removable Devices setting (BIOS Boot menu), 341
Boot USB Devices First setting (BIOS Boot menu), 341
bootable CDs, creating, 649, 652
bootable DVDs, creating, 649
bootmgr.exe, 1062
bootstrap loader, 285
bootstrap troubleshooting approach, 1087-1088
bouncing keystrokes, 804
boutique heatsinks, 156
boxed processors, 998-999
branch prediction, 69, 101
branch target buffer (BTB), 101
BraTattin, Walter, 6, 12
Break codes, 807
bridges, wireless, 888
brightness (monitors), 715
Brightness Steps setting (BIOS Advanced Flat Panel Display menu), 326
broadband technology
CATV (cable TV)
cable bandwidth, 835
cable modems, 833-835
costs, 836
explained, 832
cellular broadband
3G mobile broadband, 840
4G mobile broadband, 840-841
comparison of access types, 846-847
dsl (digital subscriber line), 836
ADSL (Asymmetric DSL), 838
availability, 837
CAP (carrierless amplitude/phase), 837
costs, 839-840
dmt (discrete multitone), 837
dslam (DSL access multiplexer), 837
how it works, 836-837
low-pass filters, 837
SDSL (Symmetrical DSL), 838
security, 838
self-installing, 838-839
transceivers, 837
VDSL (Very High-Data-Rate DSL), 838
broadband technology

explained, 832
ISDN (Integrated Services Digital Network), 844-845
leased lines, 845-846
satellite broadband explained, 841-842
HughesNet, 842
performance issues, 844
StarBand, 843
WildBlue, 843
service interruptions, 849
status LEDs, 851-852
wireless broadband, 840
Broadwater (96x) chipsets, 217
Broadwell processors, 116, 229-231
brown power switch connector wires, 927
BSOD (Blue Screen Of Death) errors, 1053
BTB (branch target buffer), 101
BTS DriverPacks, 444
BTX motherboards, 174-177
buckling spring keyboards, 802-804
buffers, TLB (translation lookaside buffer), 65
bugs. See also troubleshooting bug checks, 1053
processor bugs, 94-95
building systems. See system assembly
Bulldozer FX processors, 134-137
bumpless build-up layer (BBUL), 80
burning
CDs, 586, 648
ROM (read-only memory), 288
burn-in testing, 1054-1055
burst EDO (BDO), 367
bus masters, 65
busmasters ATA (AT Attachment), 429
busmaster DMA (direct memory access), 430
Bus Overrides settings (BIOS Setup), 330
bus snooping, 65
buses
address buses, 48-49
AGP (accelerated graphics port), 270
bandwidth, 257-261
bus masters, 65
bus snooping, 65
definition of, 255
DIB (Dual Independent Bus) architecture, 70
DMA (direct memory access), 276
DMI (Direct Media Interface), 256
EISA (Extended Industry Standard Architecture), 263, 273
external data buses, 48
HyperTransport bus, 201
identifying, 262
internal data buses, 49
I/O port addresses, 276-277
IRQs (interrupt request channels)
8-bit ISA bus interrupts, 272
16-bit ISA/EISA/MCA bus interrupts, 273-274
Advanced Programmable Interrupt Controller, 275
conflicts, 275
disabled interrupt sensing, 271
interrupt sharing, 272
maskable interrupts, 272
PCI interrupts, 275
PCI IRQ Steering, 272
ISA (Industry Standard Architecture), 262, 272-273
local buses, 263-264
MCA (MicroChannel Architecture), 262, 273
NICs (network interface cards), 870
overclocking, 149
PCI (Peripheral Connect Interface), 256, 265-268
adapter cards, 266
board configurations, 266-267
bus types, 266
interrupts, 275
PCI Express, 256, 268-270
specifications, 264-265
processor buses, 255, 261-262, 363-365
S-100 bus, 15
topology, 881-882
USB. See USB (Universal Serial Bus)
VES (Video Electronics Standards Association), 264
video memory bus width, 677-678
widths, 29-30
Buscom, 34
buttons (mouse), 815
byte mode (parallel ports), 792

C
cable bandwidth, 835
cable modems, 833-835
cable select (CSEL) signals, 426
cable select (CS) pins, 426-428
cable TV. See CATV (cable TV)
CableLabs Certified cable modems, 833
cables, 871
cable distance limitations, 878-880
cable ties, 1067
choosing, 899, 1006
FIC (flex interconnect cable), 484
grounding loops, 873
hard drive cables, 536
installation, 1026-1027, 1033
keyboard cables, 811-812
modular cables, 981-982
PATA (Parallel ATA) I/O cables, 423-425
SATA (Serial ATA), 434-437
testing, 811
Thicknet, 871-872
Thinnet, 872
twisted-pair cables
building, 875-879
Category 3 cable, 874
Category 5 cable, 874
Category 6 cable, 874
Category 6a cable, 874
crossover cables, 877
STP (shielded twisted-pair), 872-873
UTP (unshielded twisted-pair), 872
wiring standards, 875-876
USB Type-C cable, 772
cache
bus snooping, 65
cache controllers, 65
direct-mapped cache, 64
explained, 58, 359-360, 1001
fully associative mapped
cache, 64
hard disk drive cache
programs, 542
hits/misses, 360
Level 1, 58, 360
cache operation, 59-60
importance of, 59
Pentium-MMX
improvements, 67
Level 2, 61, 360
Level 3, 61-62, 361
performance and design, 62-63
set associative cache, 64
speed, 65
TLB (translation lookaside
buffer), 65
write-back cache, 401
write-through cache, 64

<table>
<thead>
<tr>
<th>Cache Controllers</th>
<th>65</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caddy Load Mechanism (CD/ DVD Drives)</td>
<td>64</td>
</tr>
<tr>
<td>Cady, Walter G.</td>
<td>145</td>
</tr>
<tr>
<td>CAG (Chassis Air Guide) Design Guide</td>
<td>161</td>
</tr>
<tr>
<td>Calculating</td>
<td>66</td>
</tr>
<tr>
<td>Power Consumption</td>
<td>961-963</td>
</tr>
<tr>
<td>Video RAM</td>
<td>676-677</td>
</tr>
<tr>
<td>Calculators</td>
<td>66</td>
</tr>
<tr>
<td>9100A Electronic Calculator</td>
<td>22</td>
</tr>
<tr>
<td>IBM701 Defense Calculator</td>
<td>475</td>
</tr>
<tr>
<td>Caldera</td>
<td>25</td>
</tr>
<tr>
<td>CAM ATA (Common Access Method ATA)</td>
<td>411</td>
</tr>
<tr>
<td>Canadian Standards Agency (CSA)</td>
<td>960</td>
</tr>
<tr>
<td>Cannon Electric</td>
<td>743</td>
</tr>
<tr>
<td>Cannon, James H.</td>
<td>743</td>
</tr>
<tr>
<td>Cannon Plugs</td>
<td>743</td>
</tr>
<tr>
<td>CAP (Carrierless Amplitude/ Phase)</td>
<td>837</td>
</tr>
<tr>
<td>Capacitive Keyswitches</td>
<td>802-804</td>
</tr>
<tr>
<td>Capacity</td>
<td>802-804</td>
</tr>
<tr>
<td>ATA Drive Capacity Limitations</td>
<td>450-451</td>
</tr>
<tr>
<td>2.1 GB Barrier</td>
<td>459</td>
</tr>
<tr>
<td>2.2 TB Barrier</td>
<td>470-471</td>
</tr>
<tr>
<td>4.2 GB Barrier</td>
<td>460-462</td>
</tr>
<tr>
<td>8.4 GB Barrier</td>
<td>465-466</td>
</tr>
<tr>
<td>137 GB Barrier and Beyond</td>
<td>466-468</td>
</tr>
<tr>
<td>BIOS Commands Versus ATA Commands</td>
<td>454</td>
</tr>
<tr>
<td>BIOS Limitations</td>
<td>451-452</td>
</tr>
<tr>
<td>CHS Bit-Shift Translation</td>
<td>457-459</td>
</tr>
<tr>
<td>CHS/LBA Conversions</td>
<td>453</td>
</tr>
<tr>
<td>CHS Limitations</td>
<td>455-457</td>
</tr>
<tr>
<td>CHS Versus LBA</td>
<td>452-453</td>
</tr>
<tr>
<td>GPT (GUID Partition Table)</td>
<td>470-471</td>
</tr>
<tr>
<td>LBA Assist Translation</td>
<td>462-464</td>
</tr>
<tr>
<td>Table Of</td>
<td>450</td>
</tr>
<tr>
<td>CDs</td>
<td>570, 581-582, 586</td>
</tr>
<tr>
<td>DVDs</td>
<td>601-604</td>
</tr>
<tr>
<td>Flash Memory Cards</td>
<td>560-561</td>
</tr>
<tr>
<td>HDDs (Hard Disk Drives)</td>
<td>499-500, 537-538</td>
</tr>
<tr>
<td>Magnetic Storage</td>
<td>491-492</td>
</tr>
<tr>
<td>Card Readers</td>
<td>563-564</td>
</tr>
<tr>
<td>Care and Maintenance</td>
<td>564</td>
</tr>
<tr>
<td>See Also Troubleshooting</td>
<td>564</td>
</tr>
<tr>
<td>Active/Passive</td>
<td>1075-1076</td>
</tr>
<tr>
<td>CD/DVD Drives</td>
<td>648</td>
</tr>
<tr>
<td>CDs/DVDs</td>
<td>571, 653-654</td>
</tr>
<tr>
<td>Cleaning</td>
<td>1077</td>
</tr>
<tr>
<td>CD/DVD Drives</td>
<td>648</td>
</tr>
<tr>
<td>CDs</td>
<td>653</td>
</tr>
<tr>
<td>Chemical-Freeze Sprays</td>
<td>1078</td>
</tr>
<tr>
<td>Compressed Air</td>
<td>1078</td>
</tr>
<tr>
<td>Connectors</td>
<td>1080</td>
</tr>
<tr>
<td>Contact Cleaners/Lubricants</td>
<td>1078</td>
</tr>
<tr>
<td>Connectors</td>
<td>1080</td>
</tr>
<tr>
<td>Erasers</td>
<td>1079</td>
</tr>
<tr>
<td>Keyboards</td>
<td>812-813, 1080-1081</td>
</tr>
<tr>
<td>Keyswitches</td>
<td>800</td>
</tr>
<tr>
<td>Mice</td>
<td>821, 1080-1081</td>
</tr>
<tr>
<td>Swabs</td>
<td>1079</td>
</tr>
<tr>
<td>System Disassembly</td>
<td>1079-1080</td>
</tr>
<tr>
<td>Vacuum Cleaners</td>
<td>1079</td>
</tr>
<tr>
<td>Dust</td>
<td>1085</td>
</tr>
<tr>
<td>Heating and Cooling</td>
<td>1081-1082</td>
</tr>
<tr>
<td>Keyboards</td>
<td>811-812</td>
</tr>
<tr>
<td>Keyswitches</td>
<td>800</td>
</tr>
<tr>
<td>Mice</td>
<td>821</td>
</tr>
<tr>
<td>Monitors</td>
<td>728</td>
</tr>
<tr>
<td>Operating Environment</td>
<td>1081</td>
</tr>
<tr>
<td>Pollutants</td>
<td>1085</td>
</tr>
<tr>
<td>Power Cycling</td>
<td>1082</td>
</tr>
<tr>
<td>Power-Line Noise</td>
<td>1083-1084</td>
</tr>
<tr>
<td>Power-Protection Systems</td>
<td>985</td>
</tr>
<tr>
<td>Backup Power</td>
<td>985</td>
</tr>
<tr>
<td>Explained</td>
<td>982-984</td>
</tr>
<tr>
<td>Line Conditioners</td>
<td>985</td>
</tr>
<tr>
<td>Phone Line Surge Protectors</td>
<td>984-985</td>
</tr>
<tr>
<td>Surge Protectors</td>
<td>984</td>
</tr>
<tr>
<td>RFI (Radio-Frequency Interference)</td>
<td>1084</td>
</tr>
<tr>
<td>Safety</td>
<td>1068-1069</td>
</tr>
<tr>
<td>Static Electricity</td>
<td>1083</td>
</tr>
<tr>
<td>System Restore</td>
<td>1076</td>
</tr>
<tr>
<td>Tools</td>
<td>1063-1064</td>
</tr>
<tr>
<td>2.5&quot; ATA Drive Cables and Adapters</td>
<td>1067</td>
</tr>
<tr>
<td>3.5&quot; Drive Enclosure</td>
<td>1068</td>
</tr>
<tr>
<td>Cleaning Materials</td>
<td>1067</td>
</tr>
<tr>
<td>Data Transfer Cables and Adapters</td>
<td>1067</td>
</tr>
<tr>
<td>DMMs (Digital Multimeters)</td>
<td>1067</td>
</tr>
<tr>
<td>1070-1071</td>
<td></td>
</tr>
<tr>
<td>Electrical Testing Equipment</td>
<td>1069</td>
</tr>
<tr>
<td>Electric Screwdrivers</td>
<td>1067</td>
</tr>
<tr>
<td>1074</td>
<td></td>
</tr>
<tr>
<td>ESD (Electrostatic Discharge) Protection Kits</td>
<td>1068</td>
</tr>
<tr>
<td>Files</td>
<td>1067</td>
</tr>
<tr>
<td>Flashlights</td>
<td>1067</td>
</tr>
<tr>
<td>Hemostats</td>
<td>1067</td>
</tr>
<tr>
<td>Infrared Thermometers</td>
<td>1074-1075</td>
</tr>
<tr>
<td>Lithium Coin Cell Batteries</td>
<td>1068</td>
</tr>
<tr>
<td>Logic Probes</td>
<td>1071</td>
</tr>
<tr>
<td>Loopback Connector</td>
<td>1069-1070</td>
</tr>
<tr>
<td>Markers/Pens</td>
<td>1067</td>
</tr>
<tr>
<td>Memory Testers</td>
<td>1072-1074</td>
</tr>
<tr>
<td>Needle-Nose Pliers</td>
<td>1067</td>
</tr>
<tr>
<td>Nut Drivers</td>
<td>1065</td>
</tr>
<tr>
<td>Nylon Cable-Ties</td>
<td>1067</td>
</tr>
<tr>
<td>Outlet Testers</td>
<td>1072</td>
</tr>
<tr>
<td>Parts Grabbers</td>
<td>1065, 1075</td>
</tr>
<tr>
<td>POST CRDS</td>
<td>1067</td>
</tr>
<tr>
<td>Spare Keyboard/Mouse</td>
<td>1068</td>
</tr>
<tr>
<td>Spare Parts</td>
<td>1068</td>
</tr>
<tr>
<td>Temperature Probes</td>
<td>1074</td>
</tr>
<tr>
<td>Tool/Supply Vendors</td>
<td>1064</td>
</tr>
</tbody>
</table>
carrierless amplitude/phase (CAP), 837
CAS (column address strobe) latency, 365
cases, 997-998
cover assembly, 1033
defined, 31
mounting motherboards in, 1018-1021
no-tool cases, 1066
Cassette BASIC, 350
Category 3 cables, 874
Category 5 cables, 874
Category 6 cables, 874
Category 6a cables, 874
CATV (cable TV)
cable bandwidth, 835
cable modems, 833-835
costs, 836
explained, 832
CAV (constant angular velocity) technology, 640
CCleaner, 1077
CD audio connectors, 254
CD-DA, 618
CD drives. See also CDs
access times, 645
bootable CDs, 652
booting from, 1058
buffers/cache, 646
CAV (constant angular velocity) technology, 640
choosing, 1003-1004
CLV (constant linear velocity) technology, 640-643
data transfer rates, 640
defined, 31
DMA and Ultra-DMA, 646
drive sealing, 648
firmware updates, 654-655
history of, 570-571
interfaces, 646-647
laser operation, 573
loading mechanisms, 647
mechanical drive operation, 574-575
MultiAudio, 592
MultiPlay, 592
MultiRead, 590-592
self-cleaning lenses, 648
table of drive speeds/transfer rates, 641
troubleshooting, 1098
disc burning, 652
disc read failures, 649-652
disc write failures, 650-651
slow drive speeds, 651
CD-R capacity, 586
copy protection and technology, 584-586
disc read errors, 650-652
disc read errors, 649-652
disc write errors, 651
DRM (digital rights management), 636
explained, 583-584
For Music Use Only discs, 635
CD-RW, 588-590
copy protection, 635-636
disc read errors, 650-652
disc write errors, 651
DRM (digital rights management), 636
explained, 583-584
For Music Use Only discs, 635
CD TEXT, 579
construction and technology, 571
copy protection, 581, 635-636
DRM (digital rights management), 636
DualDisc, 624-625
EFM data encoding, 582-583
explained, 570
file systems, 628-629
HFS (Hierarchical File System), 633
High Sierra, 629-630
ISO 9660, 630-631
Joliet, 631-632
Rock Ridge, 633
UDF (Universal Disk Format), 632-633
form factor, 570
for Music Use Only discs, 635
frames, 577-578
history of, 570-571
hub clamping area, 575
Labelflash, 649
lands, 573-574
lead-in, 575
lead-out, 575
LightScribe, 649
mass production, 571-573
Mount Rainier standard, 571-572
mounting motherboards in, 1018-1021
no-tool cases, 1066
no-tool cases, 1066
weekly and monthly checklists, 1076-1077
Torx drivers, 1065
tweezers, 1065
vises/clamps, 1067
Windows install media, 1067
wire cutters, 1067
wire strippers, 1067
weekly and monthly checklists, 1076-1077
Index

Orange Book standard, 618-619
PCA (power calibration area), 575
Photo CD, 621-622
Pits, 573-574
PMA (power memory area), 575
Program area, 575
Read errors, 580-581
Ripping, 634-635
Sampling rates, 578
Scarlet Book standard (SA-CD), 623-624
Sector modes and forms, 618
Sectors, 577-578
Subcode bytes, 578-579
Super Video CDs, 623
Table of CD formats, 616-617
Technical parameters, 576-577
Tracks, 575
Troubleshooting
disc burning, 652
disc read failures, 649-652
disc write failures, 650-651
Virgin CDs, 585
White Book standard (Video CD), 622-623
CD TEXT, 579
Celeron 4 chipsets
Celeron chipsets, 103, 107-108
ATI chipsets, 231
Intel 96x series, 217
Intel 915 family, 215
Intel 925X family, 215-216
Intel 945 Express family, 216
Intel 955X, 217
Intel 975X, 217
Intel chipsets reference tables, 208-214
NVIDIA, 232
SiS chipsets, 231
ULI chipsets, 231
VIA, 232
cell phones, tethering, 849
cells, bit cells, 478
cellular broadband
3G, 840
4G, 840-841
central processing units (CPUs).
See specific processors
central switch (CS), 837
certifications
CrossfireX certified power supplies, 960
Power supply safety certifications, 960-961
SLI-ready power supplies, 960
CFast, 550
CFX12V power supply, 920
Charging Scheme setting (BIOS USB menu), 318
chassis
CAG (Chassis Air Guide) Design Guide, 161
Chassis intrusion connectors, 254
defined, 31
thermally advantaged chassis cooling fans, 159-160
maximum heatsink inlet temperatures, 160
processor ducts, 161
specifications, 160-161
Chassis Intrusion setting (BIOS Security menu), 335
checkpoint codes (POST), 1041
chemical cleaners, 1078
chemical-freeze sprays, 1078
Chernobyl virus, 295
Cherry MX switches, 799-800
chip on ceramic (COC) technology, 484
chips
chip creep, 376
CISC (complex instruction set computer), 66
EEPROM (electronically erasable programmable ROM), 290-291, 295-302
EPROM (erasable programmable ROM), 289-290
flash ROM, 290-291
keyboard controller chips, upgrading, 295
OTP (one-time programmable) chips, 288
RISC (reduced instruction set computer), 66
RTC/NVRAM (real-time clock/ nonvolatile memory) chips, 284
Super I/O chips, 244
Chips and Technologies, 194
Chipset-SATA Mode setting (BIOS SATA Drives menu), 320
chipsets
82C206 chips, 194
82C836 SCAT (Single Chip AT) chipsets, 194
AMD, 232
AMD 690 series, 236
AMD 700 series, 237-238
AMD 800 series, 237-238
AMD 900 series, 237-241
AMD 8000 (8151), 234-235
AMD A series, 241-243
AMD (ATI) 480x and 500 series, 236
integrated graphics architecture, 197
reference table, 233
ATI, 201, 231
AT motherboards, 193-194
CS8220 chipset, 194
databooks, 1000
documentation, 279-280
explained, 192-193, 999-1000
history of, 193-194
hub architecture, 199-200
HyperTransport interconnects, 201
industry control of, 26
integrated video/motherboard chipsets, 659-660
chipsets for 64-bit AMD processors, 662-663
graphics chip market share, 660
Intel chipsets
third-party chipsets for Intel processors, 662
Intel, 195, 230
3x series, 218-220
4x series, 219-220
5x series, 220-224
6x series, 224-225
7x series, 225-227
8x series, 227-229
9x series, 229-231
96x series, 217
486 chipsets, 201-202
915 family, 215
925X family, 215-216
945 Express family, 216
955X, 217
975X, 217
INDEX

82350 chipsets, 201
Extreme Graphics
Architecture, 197
model numbers, 196
North Bridge, 197-199
Pentium chipsets, 202-203
Pentium 4 chipsets, 208-214
Pentium Pro chipsets, 203-207
southbridge, 197-199
Super I/O chips, 197

NEAT (New Enhanced AT)
CS8221 chipset, 194
NVIDIA Technologies, 232, 243-244
PC/XT motherboards, 193-194
SiS (Silicon Integrated Systems), 231
Athlon/Duron chipsets, 242
MuTIOL architecture, 201
Super I/O chips, 244
ULI, 231
VIA Technologies, 201, 232, 242
video adapter chipsets, 673

CHS (cylinder head sector)
addressing
2.1 GB barrier, 459
4.2 GB barrier, 460-462
528 MB barrier, 455-457
CHS bit-shift translation, 457-459
CHS/LBA conversions, 453-454
compared to LBA (logical block address), 452-453

CIIH virus, 295
Cinavia, 638
CIRC (cross-interleave Reed-Solomon code), 580
Cirque Glidepoint, 824-825
CISC (complex instruction set computer) chips, 66
citrus-based cleaners, 1078
clamps, 1067
CL (CAS latency), 365
Clean Boot CD package, 299
clean room approach, 24
cleaning, 1077
CD/DVD drives, 648
CDs, 653
chemical-freeze sprays, 1078
compressed air, 1078
connectors, 1080
contact cleaners/lubricants, 1078
contacts, 1080
erasers, 1079
keyboards, 812-813, 1080-1081
keyswitches, 800
mice, 821, 1080-1081
swabs, 1079
system disassembly, 1079-1080
vacuum cleaners, 1079

Clear BIOS Passwords setting (BIOS Maintenance menu), 312
Clear Secure Boot Data setting (BIOS Secure Boot Configuration menu), 345
Clear Trusted Platform Module setting (BIOS Maintenance menu), 312
Clear User Password setting (BIOS Security menu), 335
Click BIOS, 309
ClickLock feature (IntelliMouse), 819
clients
client/server networks, 856-858
standard thick client, 997
standard thin client, 997
clocks, 145-147. See also overclocking
clock signals, 55, 486
clock speed, 55-58, 363
closed loop feedback mechanism, 527
cloud-based storage, 565-566
clusters, 519
CLV (constant linear velocity) technology, 640-643
CMOS battery failed (error message), 1044
CMOS checksum error <0096> Defaults loaded (error message), 1044
CMOS (Complementary Metal Oxide Semiconductor), 13
CMOS RAM addresses, 303-304
backing up, 294

batteries
modern CMOS batteries, 989-990
obsolete/unique CMOS batteries, 990-991
troubleshooting, 991-992
configuring. See Setup (BIOS) defined, 284-285
diagnostic status byte codes, 304
CmosPwd, 294
CMOSrest, 294
CMOSsave, 294
CNR (Communications and Networking Riser), 256
coaxial cables
Thicknet, 871-872
Thinnet, 872
coaxial PDIF sound card connectors, 742
COC (chip on ceramic) technology, 484
code names for processors, 95
code-free DVD players, 639
color coding
ATX motherboards, 182
power switch connectors, 927-928
Colossus, 6, 10
column address strobe (CAS) latency, 365
COM ports. See serial ports
combo adapters, 870
Command Rate setting (BIOS Performance menu), 332
commercial diagnostic software, 1054-1055
Common Access Method ATA (CAM ATA), 411
communication ports, 788
compact disc read-only memory. See CD drives; CDs
compact form factor (CFX12V) power supply, 920
CompactFlash, 549-550
Compaq
ATA. See ATA (AT Attachment)
BIOS error messages, 351
reverse engineering of IBM software, 24-25
compatibility
buses, 262
DVD drives, 627
recordable DVD, 605-606
Sound Blaster Pro sound cards, 736
compatible mode (parallel ports), 791
Complementary Metal Oxide Semiconductor (CMOS), 13
complex instruction set computer (CISC) chips, 66
component benchmarks, 54
composite ferrite heads, 480
compressed air, 1078
compressed air, cleaning keyboards with, 812
compression of sound card data, 746-747
custom cores, 137-139
custom shaders (DirectX), 702
custom computer history. See history of computers
CONFIG.SYS file, 1061
configuration documentation, 1010
hardware-assisted virtualization support, 74
HDDs (hard disk drives)
automatic drive detection, 1030-1031
explained, 1027-1028
network software, 899-900
parallel ports, 792-793
PATA (Parallel ATA), 426-429
power supply, 1023-1025
processor operating voltages, 94
SATA (Serial ATA), 443
serial ports, 788
SSDs (solid-state drives), 1027-1028
configuration jumper, 311
Configuration section (BIOS Setup)
Audio menu, 320
Onboard Devices menu, 315-317
PCI/PCIe Add-in Slots menu, 319
SATA Drives menu, 320-323
USB menu, 317-319
Video menu, 323-326
conflicts (IRQ), 275
connectors
ATA (AT Attachment), 417
floppy power connectors, 947-948
hard drive connectors, 536
keyboard/mouse interface connectors
hybrid mice, 818-819
keyboard connectors, 808-809
PS/2 mouse port, 817
troubleshooting, 812
USB (Universal Serial Bus), 818
motherboard connectors, 244-250
alternative single-row front panel connector pinouts, 248
AMR (Audio Modem Riser), 256
ATAPI-style line-in connectors, 255
card reader connectors, 255
card reader switch connector, 255
CD audio connectors, 254
card reader switch connector, 254
CNR (Communications and Networking Riser), 256
card reader switch connector, 256
front panel audio connector pinout, 252-253
front panel switch/LED connector pinouts, 246-247
IEEE 1394a connector, 252
infrared data front panel connector pinout, 253
LED and keylock connectors, 253
microprocessor fan power connectors, 255
power LED indications, 247-248
speaker connectors, 254
telephony connectors, 254
USB 1.1-2.0 header connector pinout, 249
USB 3.0 header connector pinout, 251
Wake on LAN connectors, 254
motherboard power connectors
4-pin to 8-pin +12V power connectors, 941-942
8-pin +12V power connectors, 942-943
ATX12V 2.0, 936-939
ATX/ATX12V 1.1, 931-936
backward/forward compatibility, 944-946
Dell proprietary ATX design, 946
explained, 928-929
PCG (Platform Compatibility Guide), 940-941
power switch connectors, 925-928
VMR (voltage regulator module), 939-940
parallel port connectors, 789
PATA (Parallel ATA) I/O connectors, 419-423
PCI Express x16 Graphics Power connectors, 949-953
peripheral power connectors, 946-947
PS/2-type connector, 169
SATA (Serial ATA), 434-437, 948-949
serial ports
9-pin serial port connectors, 787
9-pin-to-25-pin serial port connectors, 788
25-pin serial port connectors, 787
sound card connectors, 740-744
analog RCA, 743
aux in, 743
coaxial PDIF, 742
HDMI (High Definition Multimedia Interface), 743
line in sound card connectors, 741
line out sound card connectors, 741
microphone in connectors, 742
MIDI in/out, 743
mono in connectors, 742
optical SPDIF out, 742
Index

1116

Index

connectors

rear out sound card
connectors, 742
socketed op amp chips, 744
world clock I/O, 743
XLR input/output, 743
USB (Universal Serial Bus) connectors
Mini/Micro A/B connectors, 766
mini plugs and sockets, 766
Series A/B connectors, 766
Type-C cable, 772
USB 1.1-2.0 connectors, 764-767
wired network adapter connectors, 870-871
Conner Peripherals, Inc. 2.5" drives, 502
constant angular velocity (CAV) technology, 640
constant linear velocity (CLV) technology, 640-643
constant voltage power supply, 903
consumption of power supply, calculating, 961-963
contact start stop (CSS) design, 504
contacts, cleaning, 1078-1080
content scramble system (CSS), 637-638
contrast (monitors), 715
Control Data Corporation. See ATA (AT Attachment)
Control Mode setting (BIOS Fan Control & Real-Time Monitoring menu), 327
Control Temperature setting (BIOS Fan Control & Real-Time Monitoring menu), 327
controllers. See adapters
conventional memory, 315, 405
Cool 'n' Quiet setting (BIOS Setup), 346
CoolerMaster, 159, 813
cooling. See heating/cooling issues
copy protection
CDs, 581, 635-636
DVDs, 636-637
breakability of, 638
Cinavia, 638
CSS (content scramble system), 637-638
ProtectDisc, 638
region codes used by Blu-ray disc, 640
RPC (regional playback control), 639
copyright protection, 24
cordless input devices. See wireless input devices
Core 2 processors
chipsets
Intel -3x series, 218-220
Intel 4x series, 219-220
overview, 112-115
core audio APIs, 737-738
Core i processors (Intel)
chipsets
Intel 5x series, 220-224
Intel 6x series, 224-225
Intel 7x series, 225-227
Intel 8x series, 227-229
Intel 9x series, 229-231
Haswell architecture, 120, 152
Intel Atom, 121
Ivy Bridge architecture, 119
Nehalem architecture, 116-118
overclocking, 151
Sandy Bridge architecture, 118-119
Core Max Multiplier setting (BIOS Performance menu), 329
cores, unlocking, 148-149
cosmic ray-induced errors, 389
cover assembly (cases), 1033
CP/M, 17
CPP-GMR (current perpendicular-to-the-plane giant magneto-resistive) heads, 483
CPU at nnnn (error message), 1044
CPU C States setting (BIOS Power menu), 337
CPU Idle State setting (BIOS Performance menu), 332
CPU Voltage Override setting (BIOS Performance menu), 332
CPU Voltage Override Type setting (BIOS Performance menu), 333
CPU VREG Droop Control setting (BIOS Performance menu), 333
CPUs (central processing units). See specific processors
CPU-Z, 33, 74, 148, 196, 293, 387
crashes (head), 504
CRC (cyclical redundancy checking), 417
Creative
OpenAL, 738
Sound Blaster Pro sound cards, 736
Sound Blaster sound cards, 736
Creative ALchemy, 739
creep, 969
cross-interleave Reed-Solomon code (CIRC), 580
CrossFire, 705-707, 949-953
CrossfireX, 960
crossover UTP (unshielded twisted-pair) cables, 877
CrystalDiskInfo, 447
crystals, quartz, 142-145
current
perpendicular-to-the-plane giant magneto-resistive (CPP-GMR) heads, 483
Current Duty Cycle setting (BIOS Fan Control & Real-Time Monitoring menu), 327
Current Fan Speed setting (BIOS Fan Control & Real-Time Monitoring menu), 327
Current Reading setting (BIOS Fan Control & Real-Time Monitoring menu), 327
custom PC configurations, 995-997
audio/video editing systems, 996
gaming systems, 996
graphics systems, 995
home server systems, 996-997
home theater systems, 996
standard thick client, 997
standard thin client, 997
virtualization systems, 996

CVT16, 69
cycle times, 365
cyclical redundancy checking (CRC), 417

cycling power, 968-971
cylinder head sector addressing. See CHS addressing
cylinders, 504
Cyrix
integrated video/motherboard chipsets, 660
processors, 95
Czochralski method, 74

D
DACs (digital-to-analog converters), 678, 735
DAE (digital audio extraction). See ripping CDs
daisy chains, 426
Damping setting (BIOS Fan Control & Real-Time Monitoring menu), 327
DAO (disc-at-once) recording, 619
DASP (drive action/slave present) signals, 426
data buses. See buses
data compression, 746-747
data encoding
  EFM (eight to fourteen modulation), 582-583
  EFM+ (eight to sixteen), 604
Data Over Cable Service Interface Specification (DOCSIS), 834
data pipelines, 100-101
data recovery. See recovery
Data sector field, 508
data transfer cables, 1067
data transfer rates. See transfer rates
data zone (DVDs), 595
databooks, 1000
dataflow analysis, 69-70
DataMaster, 16
db (decibels), 734
DB-9 connectors, 870
DB-15 cable (Thicknet), 871-872
DBB (dynamic bass boost), 754
DCMA (Digital Millennium Copyright Act), 637
DC voltages
  negative voltages, 905-906
  positive voltages, 904-905
DCC (Display Data Channel), 683-684
DDR DIMMs, 378, 384
DDR SDRAM, 368-370, 675
DDR2 DIMMs, 378, 384
DDR2 SDRAM, 370-372
DDR3 DIMMs, 379, 384
DDR3 dual-channel, 86
DDR3 SDRAM, 372-374
DDR3 triple-channel, 87
DDR4 DIMMs, 379, 384
DDR4 SDRAM, 374-375
DDWG (Digital Display Working Group), 683
dead pixels (LCDs), 730
debouncing keystrokes, 804
decibels (db), 734
decimal-based multiples, prefixes for, 451
dedicated servo mechanisms, 531-532
deferred writes, 779
definition of PCs (personal computers), 21-22
De Forest, Lee, 5, 11
delayed writes, 779
Dell proprietary ATX power connectors, 946
density, areal, 492-494
depot repair, 731
depth cueing, 699
designing systems. See system assembly
Desktop Form Factors website, 999
Detected Discrete-SATA Device setting (BIOS SATA Drives menu), 320
Detected RAID Volume setting (BIOS SATA Drives menu), 320
Detected SATA Drive setting (BIOS SATA Drives menu), 321
Detected Secondary SATA Device setting (BIOS SATA Drives menu), 321
Detected Video Device Priority setting (BIOS Video menu), 324
Deutsche Industrie Norm (DIN), 796
development of computers. See history of computers
device drivers. See drivers
Device Power states, 967-968
devices, BIOS configuration, 315-319
DeviceTopology API, 737
Devil’s Canyon processors, 229-231
DHCP (Dynamic Host Configuration Protocol), 891
diagnostic software
  commercial diagnostics, 1054-1055
  commercial software, 1040
  DXDIAG, 752
  explained, 1039
  free/open-source software, 1040
  free/user-supported diagnostics, 1055
  manufacturer-supplied software, 1039
  network interface adapters, 1053
  operating system diagnostics, 1040, 1053-1054
  peripheral diagnostics software, 1040
  POST. See POST (power on self test)
diagnostic status byte codes (CMOS RAM), 304
dial-up networks, 893
DIB (Dual Independent Bus) architecture, 70
dies, 76
differential NRZ (Non Return to Zero), 434
Digi-Key, 1064
digital audio extraction (DAE). See ripping CDs
digital display interfaces
DisplayPort, 690-694
DMS-59, 686
DVI (Digital Video Interface), 683-686
HDMI (High Definition Multimedia Interface), 686-690
overview, 682-683
Digital Display Working Group (DDWG), 683
digital infrared thermometers, 979
digital micromirror device (DMD), 721
Digital Millennium Copyright Act (DCMA), 637
digital multimeters. See DMMs (digital multimeters)
Digital Research, 17, 25
digital rights management (DRM), 636
digital signal processor (DSP), 743
digital subscriber line. See DSL (digital subscriber line)
digital-to-analog converters (DACs), 678, 735
digital versatile discs. See DVDs
Digital Video Express (DIVX), 627
Digital Video Interface (DVI), 683-686
digitized sound. See Waveform audio
DIMM n (Memory Channel x Slot y) BIOS setting, 312
DIMM setting (BIOS Maintenance menu), 312
DIMMs (dual inline memory modules), 376, 1001
168-pin SDRAM DIMM, 378
DDR DIMM, 378, 384
DDR2 DIMM, 378, 384
DDR3 DIMM, 379
purchasing, 396
SDR DIMMs, 383
DIN (Deutsche Industrie Norm), 796
DIP (dual inline package) chips, 375
Direct Application Launch Button setting (BIOS Onboard Devices menu), 316
direct disc labeling systems, 649
Direct Media Interface (DMI), 86, 199, 256
direct memory access. See DMA (direct memory access)
direct overwrite, 590
direct-mapped cache, 64
DirectCompute, 670
DirectSound wrappers, 739
DirectX, 702-703, 737
disassembly for cleaning, 1079-1080
Discard Changes setting (BIOS Exit menu), 346
disc-at-once (DAO) recording, 619
discrete multitone (DMT), 837
Discrete SATA Mode setting (BIOS SATA Drives menu), 321
Discrete SATA setting (BIOS SATA Drives menu), 321
disc-stamping operation (CDs), 573
DISK BOOT FAILURE (error message), 351
disk drive power connectors, 946-947
DISKPART command, 519
disk sweep, 529
Display CTRL-P for Intel MEBX setting (BIOS Boot Display Options menu), 343
Display Data Channel (DCC), 683-684
Display F2 to Enter Setup setting (BIOS Boot Display Options menu), 343
Display F7 to Update BIOS setting (BIOS Boot Display Options menu), 344
Display F9 for Remote Assistance setting (BIOS Boot Display Options menu), 344
Display F10 to Enter Boot Menu setting (BIOS Boot Display Options menu), 344
Display F12 for Network Boot setting (BIOS Boot Display Options menu), 344
display interface, 679-680
direct digital display interfaces, 682-683
DisplayPort, 690-694
DMS-59, 686
DVI (Digital Video Interface), 683-686
HDMI (High Definition Multimedia Interface), 686-690
TV display interfaces, 695-696
VGA (Video Graphics Array), 680-682
Display switch is set incorrectly (error message), 1044
Display Power Management Signaling (DPMS), 716
DisplayMate, 726-727
DisplayPort, 690-694
displays. See monitors
distributed parity, blocked data with, 472
divide errors, 401
DIVX (Digital Video Express), 627
d-limonene, 1078
DMA (direct memory access), 276
bustmaster DMA, 430
multiword, 430
singleword, 429-430
UDMA (Ultra-DMA), 416-418
Ultra-DMA, 430
DMD (digital micromirror device), 721
DMI (Direct Media Interface), 86, 199, 256
DMMs (digital multimeters), 811, 1067, 1070-1071
back probing, 976-977
buying tips, 974-976
measuring voltage with, 976-977
DMS-59, 686
DMT (discrete multitone), 837
DOCSIS (Data Over Cable Service Interface Specification) standards, 834
documentation
chipsets, 279-280
motherboards, 279-280
physical configuration, 1010
Dolby Digital surround sound, 755
doping, 12, 75
DOS operating system
  boot process, 1061
  DOS extenders, 52
  DPMI (DOS protected mode interface), 52
  drive limitations, 468
  free and open-source DOS versions, 25
  licensing, 25
dot pitch, 710
dots per inch (DPI), 815
double data rate SDRAM. See DDR SDRAM
double distributed parity, blocked data with, 472
double-density recording, 487
double-sided memory modules, 376
DPI (dots per inch), 815
DPMI (DOS protected mode interface), 52
DPMS (Display Power Management Signaling), 716
drains (MOSFETs), 12
DRAM (dynamic RAM)
  compared to SRAM, 359
  DDR2 SDRAM, 370-372
  DDR3 SDRAM, 372-374
  DDR4 SDRAM, 374-375
  DDR SDRAM, 368-370
  explained, 357-359
  FPO DRAM, 365-366
  RDRAM, 375
  SRAM, 367-368
DR-DOS, 25
drive action/slave present (DASP) signals, 426
DriverPacks, 444
drivers. See also BIOS
  defined, 24
  sound card drivers, 747
  video drivers, 727
drives. See CD drives; DVD drives; floppy drives; HDDs (hard disk drives)
DRM (digital rights management), 636
Dropbox, 566
DSK (Dvorak Simplified Keyboard), 811
DSL (digital subscriber line)
  ADSL (Asymmetric DSL), 838
  availability, 837
  CAP (carrierless amplitude/phase), 837
  costs, 839-840
  DMT (discrete multitone), 837
  DS-LAM (DSL access multiplexer), 837
  how it works, 836-837
  low-pass filters, 837
  SDL (Symmetrical DSL), 838
  security, 838
  self-installing, 838-839
  transceivers, 837
  VDSL (Very High Data Rate DSL), 838
  DSLAM (DSL access multiplexer), 837
  DSP (digital signal processor), 743
  DTS Surround sound, 755
  DTX motherboards, 186
dual-cavity PGA package, 103
dual-channel memory, 388
dual-core processors. See multicore processors
Dual Independent Bus architecture (DIB), 70
dual inline memory modules. See DIMMs (dual inline memory modules)
dual inline package (DIP) chips, 375
dual-drive PATA (Parallel ATA) configuration, 426-429
dual-GPU scene rendering
  AMD CrossFire, 705-707
  AMD Eyefinity, 706
  NVIDIA SLI, 704-705
  PCIe lanes, 706-707
  video RAM size, 707
dual-head graphics adapters, 722
dual-link DVI (Digital Video Interface), 684
dual rank memory modules, 376
dual-speed switches, 885
Dualview, 722-723
DualDisc, 624-625
Duron (AMD)
Duron processors
  chipsets
    nForce family, 243-244
    reference table, 233
    SiS chipsets, 242
  overview, 123
dust, 1078, 1085
Duty Cycle Increment setting (BIOS Fan Control & Real-Time Monitoring menu), 327
DVD-5 discs, 601
DVD-9 discs, 601
DVD-10 discs, 601
DVD-18 discs, 601
DVD CCA (DVD Copy Control Association), 636
DVD drives. See also DVDs
  access times, 645
  BD drive speed, 644
  buffers/cache, 646
  choosing, 1003-1004
  compatibility, 627
  defined, 31
  DMA/ Ultra-DMA, 646
  drive sealing, 648
  DVD Multi specification, 612-613
  firmware updates, 654-655
  interfaces, 646-647
  loading mechanisms, 647
  MultiAudio, 592
  MultiPlay, 592
  MultiRead, 590-592
  self-cleaning lenses, 648
  speed, 641-645
  troubleshooting, 1098
  disc burning, 652
  disc read failures, 649-652
  disc write failures, 650-651
  slow drive speeds, 651
DVD Forum, 593
DVD Multi, 612-613
DVD-R, 608
DVD-R DL, 608-609
DVD+R, 610-612
DVD+R DL, 612
DVD-RAM, 606-608
DVD-RW, 609-610
DVD+RW, 610-612
DVD+RW Alliance, 593
DVD-Video, 593
DVDs
- audio data information, 598-599
- bootable DVDs, 649
- capacity, 601-604
- care and maintenance, 653-654
- construction and technology, 593-595
- copy protection, 636-637
  - Blu-ray region codes, 640
  - breakability of, 638
  - Cinavia, 638
  - CSS (content scramble system), 637-638
  - ProtectDisc, 638
  - RPC (regional playback control), 639
- data zone, 595
- DIVX (Digital Video Express), 627
- DVD-5, 601
- DVD-9, 601
- DVD-10, 601
- DVD-18, 601
- DVD Forum, 593
- DVD-R, 608
- DVD-R DL, 608-609
- DVD+R, 610-612
- DVD-RAM, 606-608
- DVD+R DL, 612
- DVD-RW, 609-610
- DVD+RW, 610-612
- DVD+RW Alliance, 593
- DVD Video, 593
- EFM+ data encoding, 604
- error handling, 599-600
- explained, 592-593
- frames, 598-599
- HD-DVD, 616
- history of, 593
- hub clamping area, 595
- Labelflash, 649
- lead-in zone, 595
- lead-out zone, 595
- LightScribe, 649
- media compatibility, 605-606
- OTP (opposite track path), 601
- playing on PCs, 627-628
- PTP (parallel track path), 601
- sectors, 598-599
- table of recordable DVD standards, 625-627
- table of DVD formats/standards, 625-627
- edge-triggered interrupt sensing, 271
- EDID Data Source setting (BIOS Advanced Flat Panel Display menu), 326
- EDO RAM (extended data output RAM), 366-367
- eDP Data Rate setting (BIOS Advanced Flat Panel Display menu), 326
- eDP Interface Type setting (BIOS Advanced Flat Panel Display menu), 326
- EEPROM (electronically erasable programmable ROM) flash ROM upgrades, 295-296
- ASUS USB BIOS Flashback, 298
- automated bootable media images, 298
- BIOS Setup executable upgrades, 297-298
- emergency flash ROM recovery, 300-302
- safety, 300
- user-created bootable media, 299-300
- Windows executable upgrades, 296
- write protection, 295
- overview, 290-291, 357
- EFI (Extensible Firmware Interface), 307
- EFM (eight to fourteen modulation) data encoding, 582-583
- EFM+ (eight to sixteen) data encoding, 604
- El Torito support, 649
- electric screwdrivers, 1067, 1074
- electrical costs, 969-970
- Electrical Numerical Integrator and Calculator (ENIAC), 10
- electrical testing equipment, 1069
- electrically erasable programmable ROM (EEPROM), 357
electricity. See PSUs (power supply units)
electroforming, 572
electromagnetic theory, 55
electromagnetism, 476
electronically erasable
programmable ROM
(EEPROM), 290-291
electrostatic discharge (ESD)
protection, 1009-1010, 1068
embedded servo mechanisms,
530-531
Enabled state (APM), 965
encoders/decoders (endecs), 486
encoding schemes, 478
comparison of, 489-490
EFM (eight to fourteen
modulation) data encoding,
582-583
EFM+ (eight to sixteen) data
encoding, 604
explained, 486-487
FM (frequency modulation),
487
MFM (Modified Frequency
Modulation), 487
RLL (run length limited),
488-489
endecs, 410, 486
EndpointVolume API, 737
Energy 2000 standard, 716
energy-saving features
DPMS (Display Power
Management Signaling), 716
Energy Star standard, 716, 965
Energy Star standard, 716, 965
Englebart, Douglas, 814
Enhanced 3DNow!, 69
Enhanced 101-key keyboards,
795-796
Enhanced Capabilities (ECP)
parallel ports, 792
Enhanced Consumer IR setting
(BIOS Onboard Devices
menu), 316
Enhanced Disk Drive
(EDD), 457
Enhanced Halt State (C1E)
setting (BIOS Power
menu), 337
Enhanced Intel SpeedStep
Technology setting (BIOS
Power menu), 338
Enhanced Parallel Port
(EPP), 792
Enhanced SuperSpeed USB
(USB 3.1), 771-772
ENIAC (Electrical Numerical
Integrator and Calculator), 10
environmental acclimation
(HDDs), 534
environmental audio
extensions (EAX), 739
EPP (Enhanced Parallel
Port), 792
EPROM (erasable
programmable ROM), 289-290
EPS power supply, 917-918
eraser, 289, 1079
ergonomic keyboards, 811
Ergonomic Resources, 811
error correcting code (ECC),
391-392, 472, 510-511
error handing
CD errors, 580-581
DVD errors, 599-600
Error loading operating system
(error message), 353
errors. See also troubleshooting
ACPI (Advanced Configuration
and Power Interface), 348
BIOS error messages
AMI BIOS, 351
Award BIOS, 351
Compaq BIOS, 351
explained, 348-349
IBM BIOS, 350-351
Insyde BIOS, 352
Phoenix BIOS, 352
CD read errors, 580-581
DVD read errors, 599-600
Fatal Exception, 1091
MBR boot error messages, 352
Error loading operating
system, 353
Invalid partition table, 353
Missing operating system,
353
memory errors, 401
Missing operating system,
1096
POST errors. See POST (power
on self test)
soft errors, 358
STOP errors, 1090
eSATA Controller Mode setting
(BIOS SATA Drives menu), 321
eSATA (external SATA), 439-441
eSATA Ports setting (BIOS SATA
Drives menu), 321
eSATA Port x Hot Plug
Capability setting (BIOS SATA
Drives menu), 321
eSATAp (Power Over eSATA),
441-443
eSATA USB Hybrid Port
(EUHP), 441
ESD (electrostatic discharge)
protection, 1009-1010, 1068
Estridge, Don, 16
Ethernet, 859
10 Gigabit Ethernet
(10GBASE-T), 861-862
cables. See cables
development of, 7
explained, 860
Fast Ethernet, 860-861
Gigabit Ethernet, 861
hubs, 884-885
switches, 883-884, 899
address storing, 884
compared to hubs, 884-885
dual-speed, 885
managed/unmanaged, 883
placement of, 886
ports, 885
power-saving features, 885
Wi-Fi (Wireless Fidelity)
802.11a, 864-865
802.11ac, 867
802.11ad, 868
802.11b, 863-864
802.11g, 864
802.11n, 865-867
access points, 887
DHCP support, 891
explained, 862-863
network speeds, 867
NICs (network interface
cards), 887-888
point-to-point topology,
889
security, 889-891
signal boosters, 888
specialized antennas, 888
star topology, 888
users per access point, 982
wireless bridges, 888
wireless repeaters, 888
EUHP (eSATA USB Hybrid Port), 441
evolution of computers. See history of computers
evolved high speed packet access (HSPA+), 840-841
Excavator processors, 137
Execute Disable Bit setting (BIOS Security menu), 335
exFAT, 519, 563
Exit Discarding Changes setting (BIOS Exit menu), 346
Exit menu (BIOS Setup), 345-346
Exit Saving Changes setting (BIOS Exit menu), 346
expanded ATX motherboards, 182
extended ATX power supply, 918
extended data out RAM (EDO RAM), 366-367
Extended Industry Standard Architecture (EISA) buses, 263, 273
extended memory, 315
extenders (DOS), 52
Extensible Firmware Interface (EFI), 307
external cache, 360
external data buses, 48
External eSATA Port setting (BIOS SATA Drives menu), 321
external hubs, 760
external SATA (eSATA), 439-441
external speakers. See speakers
extra-high density (ED) floppy format, 496
extranets, 855
Extreme Graphics Architecture, 197
Eyefinity, 670, 706
EZ Update, 296

F
F7 BIOS Flash Update, 297
Face Wizard, 293
Faggin, Frederico, 34-35
Failsafe Watchdog setting (BIOS Performance menu), 329
failures (memory)
   hard fails, 389
   soft errors, 389-390
failures (power),
   troubleshooting, 972-973
diagnostic procedures, 973
digital infrared thermometers, 979
DMMs (digital multimeters)
   back probing, 976-977
   buying tips, 974-976
   measuring voltage with, 976-977
inadequate cooling, 973-974
overloaded power supply, 973
power supply testers, 977-978
variable voltage transformers, 979-980
Fan Control & Real-Time Monitoring menu (BIOS Setup), 327-328
fan power connectors, 255
Fan Type setting (BIOS Fan Control & Real-Time Monitoring menu), 327
Fan Usage setting (BIOS Fan Control & Real-Time Monitoring menu), 327
fans, 159-160
Faraday, Michael, 476
Fast Boot setting (BIOS Boot menu), 341
Fast Ethernet, 860-861
Fast Mode parallel ports, 792
Fast Page Mode DRAM (FPO DRAM), 365-366
Fast Startup mode, 1063
Fastchip, 290
FAT (file allocation table), 519
FAT32, 519
FAT64, 519, 563
fatal errors, 1040
fatal exception errors, 401, 1091
fathers (CD), 572
fault tolerance
   ECC (error correcting code), 391-392
   parity checking, 390-391
FC-PGA (flip-chip pin grid array), 79
FDDI (Fiber Distributed Data Interface), 882
FDI (Flexible Display Interface), 86
Federal Communications Commission (FCC), 961
Femto air bearing sliders, 485-486
ferrite read/write heads, 480
FHSS (frequency hopping spread spectrum), 868
Fiber Distributed Data Interface (FDDI), 882
fiber to the curb (FTTC), 838
fiber to the home (FTTH), 838
fiber to the neighborhood (FTTN), 838
fiber to the premises (FTTP), 838
FIC (flex interconnect cable), 484
fields, magnetic, 477-478
file allocation table (FAT), 519
file systems
   CD file systems, 628-629
   HFS (Hierarchical File System), 633
   High Sierra, 629-630
   ISO 9660, 630-631
   Joliet, 631-632
   Rock Ridge, 633
   UDF (Universal Disk Format), 632-633
exFAT, 519
FAT, 519
FAT32, 519
flash memory, 562-563
NTFS (Windows NT File System), 519
files
   AUTOEXEC.BAT, 1061
   CONFIG.SYS, 1061
   hiberfil.sys, 1063
   MSDOS.SYS, 1061
   Ntbtlog.txt, 1062
files (metal), 1067
filters
air filters, 532-533
low-pass filters, 837
polarizing LCD filters, 716-717
FireWire
explained, 775-776
FireWire 400, 776-777
FireWire 800, 776-778
FireWire 3200, 778
hot-plugging, 779-782
tailgates, 417
firmware updates, 282, 291, 654-655, 672
"First Draft of a Report on the EDVAC" (von Neumann), 6
first-party memory modules, 395
Fixed Disk Boot Sector setting (BIOS Maintenance menu), 312
fixed disk drives. See HDDs (hard disk drives)
Flash-based SSDs, 554-555
flash memory
card capacities, 560-561
card readers, 563-564
CFast, 550
CompactFlash, 549-550
comparison of, 559-561
development of, 548
device sizes, 549
explained, 356, 547-549
file systems, 562-563
Flash-based SSDs, 554-555
keychain devices, 547
Lexar Memory Stick PRO, 552
Lexar Memory Stick PRO Duo, 552
MMC (MultiMediaCard), 551
NAND (Not AND), 548
NOR (Not OR), 548
PC Card, 553
ReadyBoost support, 564-565
SD (SecureDigital), 552
SmartMedia, 551
Sony Memory Stick, 552
Sony Memory Stick Micro, 552
Sony Memory Stick PRO-XC, 552
speed classes, 561-562
SSD (solid-state drive)
applications, 557-558
defined, 553
thumb devices, 547
USB flash drives, 558-559
xD-Picture Card, 553
XQD, 550-551
flash ROM, 290-291
recovery, 300-302
upgrading, 295-296
ASUS USB BIOS Flashback, 298
automated bootable media images, 298
BIOS Setup executable upgrades, 297-298
security, 300
user-created bootable media, 299-300
Windows executable upgrades, 296
write protection, 295
Flash Update Sleep Delay setting (BIOS Power menu), 338
flashlights, 1067
Flat Panel Configuration Changes setting (BIOS Advanced Flat Panel Display menu), 325
Flat Panel Display-Link (FPD-Link), 682
flat shading, 697
flex interconnect cable (FIC), 484
FlexATX motherboards, 184-186
FlexATX power supply, 922-924
Flexible Display Interface (FDI), 86
flip-chip pin grid array (FC-PGA), 79
floating point units, 94
Floppy Controller setting (BIOS Onboard Devices menu), 316
Floppy disks(s) fail (error message), 1044
floppy drives, 566-567
ED (extra-high density) floppy format, 496
power connectors, 947-948
Flowers, Thomas, 6, 10
FLR Capability setting (BIOS PCI/PCle Add-in Slots menu), 319
fluid dynamic bearings, 535
flux, 478
FM encoding, 487
FM synthesis, 746
FMA4, 69
foam element keyswitches, 800
For Music Use Only discs, 635
Force Onboard LAN Disable setting (BIOS Maintenance menu), 312
Force Secure Boot Defaults setting (BIOS Secure Boot Configuration menu), 345
ForceWare v81.85 (NVIDIA), 704
foreign language keyboard layouts, 807-808
FORMAT command, 515
form factors
defined, 907, 997
Form Factors website, 182
HDDs (hard disk drives)
1" drives, 503
1.8" hard drives, 503
2.5" hard drives, 502-503
3.5" half-height drives, 502
5.25" drives, 502
table of, 500-502
motherboard form factors. See motherboards
power supply form factors
ATX/ATX12V, 910-913
CFX12V, 920
EPS/EPS12V, 917-918
explained, 907-908
Flex ATX, 922-924
LFX12V, 922
proprietary standards, 909
PS3, 914
SFX/SFX12V, 913-917
table of, 909
TFX12V, 918-920
Form Factors website, 182
formatting HDDs (hard disk drives)
high-level formatting, 515-516, 520
low-level formatting, 515-516
standard recording, 516
ZBR (zoned-bit recording), 516-518
partitions, 519-520
Fowler-Nordheim tunneling, 548
FPD-Link (Flat Panel Display-Link), 682
FPO DRAM (Fast Page Mode DRAM), 365-366
FPUs, 102
fractioned T-1 lines, 845
frames (DVDs), 598-599
free diagnostic software, 1055
free magnetic layers, 483
FreeDOS, 25
frequency, 864
frequency hopping spread spectrum (FHSS), 868
frequency modulation (FM) encoding, 487
frequency response, 734, 753
frequency synthesizers, 145
frequency timing generator (FTG), 145
Front Panel Audio setting (BIOS Audio menu), 320
front panel
motherboard-controlled switches, 925-927
front panel power supply AC switches, 927-928
front side bus (FSB). See buses
front panel
FTTC (fiber to the curb), 838
FTTH (fiber to the home), 838
FTTN (fiber to the neighborhood), 838
FTTP (fiber to the premises), 838
Full On state (APM), 965
dual-duplex mode, 861, 870, 885
full-size AT motherboards, 167-168
fully associative mapped cache, 64
functions (USB), 760
Fusion/HSA (Heterogeneous Systems Architecture) APUs, 137-139
Futuremark PCMark benchmark, 57
FX Bulldozer processors, 237-241
FX processors, 134-137

G
G0 Working power state, 967
G1 Sleeping power state, 967
G2/S5 Soft Off power state, 968
G3 Mechanical Off power state, 968
gaming. See also 3D graphics accelerators
APIs, 700
AMD Mantle, 703-704
DirectX, 702-703
OpenGL, 700-701
optimizing system for, 996
gang programmers, 289
ganged heads, 524
Gap sector field, 508
gates (MOSFETs), 12
GDDR2 SDRAM, 675
GDDR3 SDRAM, 675
GDDR4 SDRAM, 676
GDDR5 SDRAM, 676
GeForce SLI website, 705
Gen 2 USB (USB -3.1), 771-772
General Optimization setting (BIOS Boot menu), 342
general-purpose errors, 401
Generate New Platform Key setting (BIOS Secure Boot menu), 344
generic chips, 760
generic PCs, 28-29
genus, 699
G.hn network standard, 895
GHz (gigahertz), 41, 362
Gl (guard interval), 866
Giant Brains, or Machines That Think (Berkeley), 22
giant magneto-resistive (GMR) heads, 482-483
Gib (gigabinarybytes), 456
gigabinarybytes (GiB), 456
Gigabit Ethernet, 861
GIGABYTE, 293, 296
gigahertz (GHz), 41, 362
GIMP, 1055
glass in hard disks, 477
Glidepoint, 824-825
Global Engineering Documents, 413
global protection faults, 401
GM Vehicle Calibration Information, 290
GMR (giant magneto-resistive) heads, 482-483
Google Drive, 566
Gouraud shading, 697
GPT (GUID Partition Table), 308, 470-471
GPT Loader (Paragon), 471
GPU Boost/GPU Booster setting (BIOS Setup), 346
GPU (video graphics processor), 673
GPU-Z, 673
Grantsdale (915) chipsets, 215
Graphene-based transistors, 13
graphics. See also 3D graphics accelerators
AMD integrated graphics architecture, 197
Extreme Graphics Architecture, 197
optimizing system for, 995
graphics adapters. See video adapters
Graphics Dynamic Frequency setting (BIOS Performance menu), 329
Graphics Max Multiplier setting (BIOS Performance menu), 329
grey code, 528
green power switch connector wires, 927
grounding loops, 873
Grove, Andrew, 33
guard interval (Gl), 866
GUID Partition Table (GPT), 308, 470-471

H
half-duplex operation, 870
hand tools, 1064
3.5 drive enclosure, 1068
cleaning materials, 1067
data transfer cables and adapters, 1067
electric screwdrivers, 1067
ESD (electrostatic discharge) protection kits, 1068
files, 1067
flashlights, 1067
hemostats, 1067
lithium coin cell batteries, 1068
markers/pens, 1067
needle-nose pliers, 1067
nut drivers, 1065
nylon cable-ties, 1067
POST cards, 1067
spare keyboard/mouse, 1068
spare parts, 1068
Torx drivers, 1065
tweezers, 1065
USB/FireWire cable adapter, 1068
vises/clamps, 1067
Windows install media, 1067
wire cutters, 1067
wire strippers, 1067
HDDs (hard disk drives)
HARD DISK INSTALL FAILURE (error message), 1044-1045
Hard Disk Drive Password Prompt setting (BIOS Security menu), 335
Hard Disk Drive Password setting (BIOS Security menu), 335
hard disk drives. See HDDs (hard disk drives)
HARD DISK INSTALL FAILURE (error message), 1044-1045
Hard Disk Drive Pre- Delay setting (BIOS SATA Drives menu), 321
Hard disk(s) diagnosis fail (error message), 1045
Hard Drive Order setting (BIOS Boot menu), 342
hard error rates (HERs), 389
hard memory fails, 389
hardcards, 410
hardware-assisted virtualization support, 73
Hardware Heaven, 740
hardware resources, 1006-1007
harmonic distortion, 734, 753
Haswell architecture (Core i), 116, 120
Intel 8x series chipsets, 227-229
overclocking, 152
Haughton, Ken, 498
HDA (head disk assemblies), 505
HD-DVD, 616
HDDs (hard disk drives)
0.85" drive, 503
0.305 RAMAC (Random Access Method of Accounting and Control), 475
actuators, 504
air filters, 532-533
areal density, 492-494
ATA drive capacity limitations, 450-451
2.1 GB barrier, 459
2.2 TB barrier, 470-471
4.2 GB barrier, 460-462
8.4 GB barrier, 465-466
137 GB barrier and beyond, 466-468
BIOS commands versus ATA commands, 454
BIOS limitations, 451-452
CHS bit-shift translation, 457-459
CHS limitations, 455-457
CHS versus LBA, 452-453
CHS/LBA conversions, 453
GPT (GUID Partition Table), 470-471
LBA-assist translation, 462-464
table of, 450
changers, 536
capacity, 499-500, 537-538
choosing, 1003
configuration automatic drive detection, 1030-1031
configuration items, 536
explained, 1027-1028
costs, 500
CSS (contact start stop) design, 504
cylinders, 504
data recovery options, 505-506
defined, 31, 498
dual-drive configurations (PATA), 426-429
ECC (error correction code), 510-511
form factors 1" drives, 503
1.8" drives, 503
2.5" hard drives, 502-503
3.5" half-height drives, 502
5.25" drives, 502
table of, 500-502
head actuator mechanisms stepper motors, 526
voice-coil actuators, 526-528
heads, 479-481, 504, 524-525
air bearing, 507
automatic head parking, 532
cautions, 506
ferrite, 480
GMR (giant magneto-resistive), 482-483
HDAs (head disk assemblies), 505
head crashes, 504
head/medium interaction, 506-507
head sliders, 483-486
MIG (Metal-In-Gap), 480
MR (magneto-resistive), 481-482
PMR (perpendicular magnetic recording), 495-497
TF (thin film), 480
heating/cooling issues, 534
high-level formatting, 515-516, 520
hot-swappable drives, 781
installation, 1028-1030
load/unload mechanism, 505
logic boards, 535-536
low-level formatting, 515-516
standard recording, 516
ZBR (zoned-bit recording), 516-518
mirroring, 472-473
operating system limitations, 468-469
partitioning, 519-520
performance average access times, 542
average seek times, 500, 541
cache programs, 542
interleave, 543
lateness, 541-542
transfer rates, 539-541
platters, 504, 522
RAID (redundant array of independent disks), 471
levels, 472-474
onboard BIOS, 292
software RAID, 474

recording media, 522
  AFC (antiferromagnetically coupled), 523-524
oxide, 523
thin-film, 523

reliability
  MTBF (mean time between failures), 543
  PFA (Predictive Failure Analysis), 544
  S.M.A.R.T. (Self-Monitoring, Analysis, and Reporting Technology), 544-546
  Safe Removal settings, 781-782
  SATA drives, 320-323
sectors, 504
  512-byte sector in recent drives, 510
  Advanced Format (4K sectors), 511-513
data bytes, 508
defined, 507
fields, 508
gaps in, 508
headers/trailers, 508
head crashes, 504
head disk assemblies (HDAs), 505
head/medium interaction (HDDs), 506
headers, sector, 508
headphones, 754
heads, 476, 479-480, 504, 524-525
  air bearing, 507
  automatic head parking, 532
cautions, 506
ferrite, 480
GMR (giant magneto-resistive), 482-483
HDAs (head disk assemblies), 505
head actuator mechanisms
  servo mechanisms, 528-531
dedicated servo, 531-532
disk sweep, 529
embedded servo, 530-531
  gray code, 528
  servowriters, 528
  thermal recalibration, 529
  wedge servo, 530
stepper motors, 526
voice-coil actuators, 526-528
head crashes, 504
head disk assemblies (HDAs), 505
head/medium interaction (HDDs), 506
headers, sector, 508
headphones, 754
heads, 476, 479-480, 504, 524-525
  air bearing, 507
  automatic head parking, 532
cautions, 506
ferrite, 480
GMR (giant magneto-resistive), 482-483
HDAs (head disk assemblies), 505
head actuator mechanisms
  stepper motors, 526
  voice-coil actuators, 526-528
head crashes, 504
head sliders, 483-486
head/medium interaction, 506-507
MIG (Metal-In-Gap), 480
MR (magneto-resistive), 481-482
PMR (perpendicular magnetic recording), 495-497
servo mechanisms, 528-531
  dedicated servo, 531-532
disk sweep, 529
embedded servo, 530-531
gray code, 528
servowriters, 528
thermal recalibration, 529
wedge servo, 530
TF (thin film), 480

heating/cooling issues
  BIOS settings, 327-328
  HDD temperature acclimation, 534
  heatsinks, 152-153
  active heatsinks, 153-155
  boutique heatsinks, 156
  choosing, 1005-1006
  heatsink clips, 153
  installation, 157-158, 1011-1017
  passive heatsinks, 156
  purchasing, 155-156
  ratings and calculations, 156-157
  infrared thermometers, 1074-1075
  liquid cooling, 158-159, 1006
  maximum heatsink inlet temperatures, 160
  positive-pressure-ventilation design, 912
  power supply, 973-974
  preventative maintenance, 1081-1082
  temperature probes, 1074
  thermally advantaged chassis cooling fans, 159-160
  maximum heatsink inlet temperatures, 160
  processor ducts, 161
  specifications, 160-161
  troubleshooting, 1095

heat spreaders, 80
heatsinks, 152-153, 1005-1006
  active heatsinks, 153-155
  boutique heatsinks, 156
  heatsink clips, 153
  installation, 157-158, 1011-1017
  maximum heatsink inlet temperatures, 160
  passive heatsinks, 156
  purchasing, 155-156
  ratings and calculations, 156-157
Heaven DX11 (UniGine), 704
HelioSeal, 497
helium-filled drives, 497
help. See diagnostic software; troubleshooting
hemostats, 1067
HERs (hard error rates), 389
Hertz, Heinrich Rudolph, 55
Hertz (Hz), 734
heterogeneous adapters, 723
Heterogeneous Systems Architecture (HSA) APUs, 137-139
Hewlett-Packard 9100A electronic calculator, 22
HFC (hybrid fiber/coax) networks, 833
HFS (Hierarchical File System), 633
HGST HelioSeal, 497
hiberfil.sys file, 1063
Hibernate (S4) state, 971
Hibernation Timer setting (BIOS Power menu), 338
Hierarchical File System (HFS), 633
High Definition Multimedia Interface (HDMI), 686-690, 743
high memory area (HMA), 52
High Precision Event Timers setting (BIOS Onboard Devices menu), 316
High Sierra file system, 629-630
high-level formatting, 515-516, 520
High-Speed Rewritable CDs, 590
High-Speed USB (USB 2.0)
data rates, 763-764
technical details, 759-763
highly parallel instructions, 67
history of computers
3D graphics accelerators, 698
ATA (AT Attachment), 410-412
Atanasoff-Berry Computer, 10
CDs, 570-571
chips, 193-194
Colossus, 10
dVDs, 593
ENIAC (Electrical Numerical Integrator and Calculator), 10
flash memory, 548
floppy drives, 566
ICs (integrated circuits), 14
importance of, 22
magnetic storage, 475
microprocessors, 38-39
Moore's Law, 17
PCs (personal computers), 15-17
Apple I, 16
Apple II, 16
IBM PCs, 15-17
MITS Altair 8800 kit, 15
pointing devices, 814
processors, 33-38
recent developments, 18-19
sound cards, 736
transistors, 11-14
UNIVAC (Universal Automatic Computer), 11
vacuum tubes, 11-12
Hitachi
Global Storage Technologies, 500
helium-filled drives, 497
Super-IPS (in-place switching), 718
hits, 64, 360
HIF. See low-level formatting
HMA (high memory area), 52
Hoff, Ted, 34
hold-up time (power supply), 957
Hollerith, Herman, 475
home networks. See networks
home servers, optimizing system for, 996-997
home theater, optimizing system for, 996
HomePlug 1.0, 896
HomePlug AV, 896
HomePlug Powerline Alliance, 895
HomeGrid Forum, 895
HomePNA, 894-895
homogeneous adapters, 723
horizontal frequency, 714
host adapters. See adapters
Host Clock Frequency (MHz) setting (BIOS Performance menu), 329
Host Clock Frequency Override setting (BIOS Performance menu), 329
Host Clock Frequency setting (BIOS main menu), 313
host interface adapters. See ATA (AT Attachment); SCSI (small computer system interface)
Host Protected Area (HPA), 305-307, 416, 448-449
host-based audio signal processing, 743
hot-plugging, 767, 779-782
hot spots, 865
hot-swappable drives, 781
HP
KittyHawk, 503
LightScribe, 649
Link-5, 829
HPA (Host Protected Area), 305-307, 416, 448-449
HPUSBDisk.exe, 299
HSA (Heterogeneous Systems Architecture) APUs, 137-139
HSPA+ (evolved high speed packet access), 840-841
HT (Hyper-Threading) Technology, 70-71
HT Link Speed setting (BIOS Setup), 346
hub clamping area
CDs, 575
dVDs, 595
hubs, 758-760, 884-885
AHA (accelerated hub architecture), 199
chipset hub architecture, 199-200
ICH (I/O Controller Hub), 199
MCH (Memory Controller Hub), 199
HughesNet, 842
HWiNFO, 387, 447
HWMonitor, 1055
hybrid fiber/coax (HFC) networks, 833
hybrid mice, 818-819
hybrid processors, 69
hydrogenated amorphous silicon (a-Si), 718
Hyper Page mode memory, 366-367
Hyper-Threading Technology (HT), 70-71
HyperStreaming, 201
HyperTransport bus, 201
Hyper-V Client, 73
Hz (Hertz), 734

IA-32 mode, 50-52
IA-32e 64-bit extension mode, 52-54
IA-64 processors, 39
IBM
305 RAMAC (Random Access Method of Accounting and Control), 475
726 Tape Unit, 475
8088 processors, 96-97
BIOS error messages, 350-351, 1048-1053
development of magnetic storage, 475
history of IBM PCs, 15-17
IBM701 Defense Calulator, 475
MicroDrive, 503
PC-AT (PC Advanced Technology), 7
PS/2 mouse port, 817
TrackPoint, 822-824
IBM clones, 21, 97
IBM compatibles, 21
ICH (I/O Controller Hub), 199
iCOMP (Intel Comparative Microprocessor Performance) index, 57
ICs (integrated circuits), 14
ID error detection (IED) codes, 598
IDE (Integrated Drive Electronics). See ATA (AT Attachment)
IDENTIFY DEVICE command, 446
IDENTIFY DRIVE command, 429, 446
IDs
ID sector field, 508
PnP (Plug and Play) device IDs, 347
IEC (International Electrotechnical Commission), 491, 959
IED (ID error detection) codes, 598
IEEE (Institute of Electrical and Electronic Engineers)
802.11a, 864-865
802.11ac, 867
802.11ad, 868
802.11b, 863-864
802.11g, 865
802.11n, 865-867
IEEE 1284, 790-791
IEEE 1394
1394a, 252, 776-777
1394b 53200, 778
1394b, 777-778
explained, 647, 775-776
hot-plugging, 779-782
iFeel Mouse (Logitech), 816
FLASH.EXE, 299
IGD DVMT Memory setting (BIOS Video menu), 324
IGD Flat Panel setting (BIOS Video menu), 324
IGD Primary Video Port setting (BIOS Video menu), 324
IGD Secondary Video Port setting (BIOS Video menu), 324
IGFX Multi-Monitor setting (BIOS Setup), 346
IHS Standards Store, 413
inductive power, 958
industry control
PC hardware, 26-28
PC software, 23-25
white-box systems, 28-29
Industry Standard Architecture (ISA) buses, 262, 272-273
infrared data front panel connector pinout, 253
infrared (IR) input devices, 828
infrared thermometers, 979, 1074-1075
infrastructure mode, 887
initial program load (IPL) ROM, 292
Innoventions, 400
in-plane switching (IPS), 718
input devices
BIOS configuration, 315-319
choosing, 1004
keyboards, 795
keys, 103-key, 796-798
buckling spring keyboards, 802-804
choosing, 813
cleaning, 812-813, 1080-1081
connectors, 808-809, 812
defined, 31
DSK (Dvorak Simplified Keyboard), 811
Enhanced 101-key, 795-796
ergonomic, 811
international layouts, 807-808
key matrix, 804
key numbers, 806-807
keyboard interface, 804-805
keyswitch design, 798-804
scan codes, 806-807
skins, 813
touch keyboards, 804
troubleshooting, 811-812
typematic functions, 805-806
USB (Universal Serial Bus), 810
mice
ball-driven mice, 815
buttons, 815
cleaning, 821, 1080-1081
components, 814-815
defined, 31
history of, 814
hybrid mice, 818-819
keyboard/mouse interface connectors, 808-809
manufacturers, 814
optical mice, 815-817
PS/2 mouse port, 817
scroll wheels, 819
sensitivity, 815
touch-sensitive mice, 820
troubleshooting, 821
USB (Universal Serial Bus), 818
touch pads, 824-825
touchscreen technology, 826-827
trackballs, 814, 825-826
TrackPoint, 822-824
wireless, 827
Bluetooth, 828
IR (infrared), 828
multiple devices with single tranceiver, 829
power management, 828-829
proprietary radio frequency, 828
troubleshooting, 829

input range (power supply), 957

inSSIDer, 1084
installation
cables, 1033
CD/DVD firmware, 655
DSL (digital subscriber line), 838-839
expansion cards, 1033
HDDs (hard disk drives), 1028-1030
heatsinks, 157-158, 1011-1017
memory modules, 1017
motherboard cables, 1026-1027
motherboards, 1018-1021
NICs (network interface cards), 898
operating systems, 1035-1036
power supply, 1023-1025
processors, 1011-1017
RAM (random access memory), 397-398
SSDs (solid-state drives), 1028-1030
troubleshooting, 1037
video adapters, 1031
Institute of Electrical and Electronic Engineers. See IEEE instruction sets (math coprocessors), 94

Insyde BIOS messages, 352

INT13h
BIOS CHS parameter limits, 455
commands, 454
INTA# interrupts, 275
INTB# interrupts, 275
INTC# interrupts, 275
INTD# interrupts, 275
integral cache, 360
Integral Periodicals 1.8" drives, 503
integral power supply AC switches, 927
integrated adapters, 1002
integrated audio chipsets, 748-749
integrated circuits (ICs), 14
Integrated Drive Electronics (IDE). See ATA (AT Attachment)
integrated graphics architecture (AMD), 197
Integrated Graphics Device setting (BIOS Video menu), 325
Integrated Services Digital Network (ISDN), 844-845
integrated video, 663-664
AMD, 667-670
Intel, 665-667
integrated video/motherboard chipsets, 659-660
chipsets for 64-bit AMD processors, 662-663
graphics chip market share, 660
Intel chipset integrated video, 660-661
third-party chipsets for Intel processors, 662
Integrator Toolkit (Intel), 293
Intel
Azalia HD Audio, 749
BTX motherboards, 174-177
chipsets, 195
3x series, 218-220
4x series, 219-220
5x series, 220-224
6x series, 224-225
7x series, 225-227
8x series, 227-229
9x series, 229-231
96x series, 217
486 chipsets, 201-202
915 family, 215
925X family, 215-216
945 Express family, 216
955X, 217
975X, 217
82350 chipsets, 201
hub architecture, 199-200
integrated video, 660-661
Intel Extreme Graphics Architecture, 197
model numbers, 196
North Bridge, 197-199
Pentium 4 chipsets, 208-214
Pentium chips, 202-203
Pentium Pro chipsets, 203-207
southbridge, 197-199
Super I/O chips, 197
DVMT (Dynamic Video Memory Technology), 677
Extreme Graphics Architecture, 197
hardware industry control, 26-28
industry control, 27
integrated video, 660, 665-667
Integrator Toolkit, 293
Intel VT-D, 74
Intel VT-x, 74
Processor Frequency ID Utility, 148
Processor Identification Utility, 148
processors, 43-45, 115
286, 97
386, 98-99, 201-202
486, 80-83, 99 201-202
8086, 95-96
8088, 96-97
4004, 34
8008, 35
8085, 35
8086, 36
8088, 36
Celeron, 103, 107-108
code names, 95
Core 2, 112-115
development of, 34, 37-39
Intel Core i, 116-121, 151-152
Index

Intel

Itanium, 39
Pentium, 100-102
Pentium II, 103-106
Pentium III, 103, 106-107
Pentium 4, 108-109
Pentium 4 Extreme Edition, 110
Pentium D, 110-113
Pentium Extreme Edition, 110-113
Pentium Pro, 103-104
specifications, 40-45
RTS2011LC cooling system, 159
Thunderbolt technology, 782-784
Turbo Boost, 333-334
Intel Chipset Identification Utility, 196
Intel Comparative Microprocessor Performance (iCOMP) index, 57
Intel-compatible processors
AMD Athlon, 122-123
AMD Athlon MP, 124
AMD Athlon XP, 124
AMD Duron, 123
AMD K5, 102-103
AMD K6, 69, 122
AMD K6-2, 122
AMD K6-3, 122
AMD Sempron, 128
NexGen Nx586, 121
Intel Dynamic Power Technology setting (BIOS Power menu), 338
Intel Enhanced Debug setting (BIOS Maintenance menu), 312
Intel Graphics Performance Analyzers setting (BIOS Video menu), 325
Intel Hyper-Threading Technology setting (BIOS main menu), 313
Intel Rapid Start Technology setting (BIOS Power menu), 339
Intel Trusted Execution Technology setting (BIOS Security menu), 335
Intel Turbo Boost Technology setting (BIOS Performance menu), 333
Intel Virtualization Technology setting (BIOS Security menu), 335
Intel VT-D, 74
Intel VT-x, 74
IntelliMouse, 815, 819
interference
RFI (radio-frequency interference), 1084
speakers, 754
interlaced mode, 715
interleaving, 366, 543
Internal 91XX Blue SATA setting (BIOS SATA Drives menu), 321
internal Level 1 cache. See Level 1 cache
internal Level 2 cache. See Level 2 cache
Internal PLL Voltage Override setting (BIOS Performance menu), 329
internal registers, 49
Internal SPDEF/DMIC setting (BIOS Onboard Devices menu), 316
Internal UEFI Shell setting (BIOS Boot menu), 342
International Electrotechnical Commission (IEC), 491, 959
international keyboard layouts, 807-808
Internet connections, 850, 855
broadband technology
CATV (cable TV), 832-836
cellular broadband, 840-841
comparison of access types, 846-847
DSL (digital subscriber line), 836-840
explained, 832
ISDN (Integrated Services Digital Network), 844-845
leased lines, 845-846
satellite broadband, 841-844
service interruptions, 849
status LEDs, 851-852
wireless broadband, 840
dialup modems
asynchronous versus synchronous communications, 847
explained, 847
routers, 850-851
security
explained, 848-849
routers, 850-851
service interruptions, 849
shared connections, 850
troubleshooting, 1091
Internet Protocol (IP), 892
Internetwork Packet Exchange (IPX), 893
interpolation, 580
interrupt request channels.
See IRQs (interrupt request channels)
interrupt sharing, 272
intrarnets, 855
Invalid partition table (error message), 353
Inverter Frequency (Hz) setting (BIOS Advanced Flat Panel Display menu), 325
Inverter Polarity setting (BIOS Advanced Flat Panel Display menu), 325
I/O buses. See buses
I/O Controller Hub (ICH), 199
IOH (I/O Hub), 86
ion bombardment, 12
IP (Internet Protocol), 892
IPL (initial program load) ROM, 292
IPS (in-plane switching), 718
IPX (Internetwork Packet Exchange), 893
IR (infrared) input devices, 828
iron oxide
in hard disks, 477
in recording media, 523
IRQs (interrupt request channels)
8-bit ISA bus interrupts, 272
16-bit ISA/EISA/MCA interrupts, 273-274
Advanced Programmable Interrupt Controller (APIC), 275
conflicts, 275
device-triggered interrupt sensing, 271
interrupt sharing, 272
maskable interrupts, 272
PCI interrupts, 275
PCI IRQ Steering, 272
sharing, 275

IRs (infrared thermometers), 1074-1075
ISA (Industry Standard Architecture) buses, 262, 272-273
ISDN (Integrated Services Digital Network), 844-845
Isobuster, 633
ISO (International Organization for Standardization) 9660 standard, 630-631
isolating memory defects, 403-405
Itanium processors, 39
ITX motherboards, 187-189
Ivy Bridge architecture (Core i), 119
overclocking, 151
Intel 7x series chipsets, 225-227
Iwasaki, Shun-ichi, 495
Japan Industrial Partners, 552
JBOD (just a bunch of disks), 472
JEDEC (Joint Electron Device Engineering Council), 361-362, 551
jitter, 757
Jobs, Steve, 7, 16, 814
Joint Electron Device Engineering Council (JEDEC), 361-362, 551
Joliet file system, 631-632
Jscreenfix, 730
jumper settings (ATA), 427
just a bunch of disks (JBOD), 472
K
K5 processors (AMD), 102-103
K6 processors (AMD), 69, 122
K6-2 processors (AMD), 122
K6-3 processors (AMD), 122
K7 processors (AMD), 122
Athlon, 122-123
Athlon MP, 124
Athlon XP, 124
Duron, 123
K8 processors (AMD)
Athlon 64, 124-128
Athlon 64 FX, 124-130
Athlon 64 X2, 128-130
Athlon X2, 128-130
Sempron, 128
K10 processors (AMD), 130-134
K11 (Bulldozer FX) processors, 134-137
Katmai New Instructions (KNI), 68
Kaveri core, 137
Key Exchange Key (KEK) setting (BIOS Secure Boot Configuration menu), 345
key matrix, 804
key numbers (keyboards), 806-807
keyboard controller chips, upgrading, 295
Keyboard is locked out – Unlock the key (error message), 1045
Keyboarderror or no keyboard is present (error message), 1045
keyboards, 795
104-key, 796-798
buckling spring keyboards, 802-804
choosing, 813, 1004
cleaning, 812-813, 1080-1081
connectors, 808-809, 812
defined, 31
DSK (Dvorak Simplified Keyboard), 811
Enhanced 101-key, 795-796
ergonomic, 811
international layouts, 807-808
key matrix, 804
key numbers, 806-807
keyboard interface, 804-805
keyswitch design
capacitive, 802-804
foam element, 800
membrane, 801-802
pure mechanical, 798-800
rubber dome, 801
troubleshooting, 812
KeyTronicEMS, 800-801
Kilby, Jack, 6, 14
Kingston FCR-HS3 Card Reader/Writer, 563-564
KittyHawk, 503
Klamath, 104
K-Lite Codec Pack, 628
KNI (Katmai New Instructions), 68
known-good spare troubleshooting technique, 1087
Ko
L2 Cache RAM setting (BIOS main menu), 313
L2 cache. See Level 2 cache
L3 Cache RAM setting (BIOS main menu), 313
Labelflash, 649
Lakeport chipsets (Intel), 216
Lancaster, Don, 7
lands, 85
  CDs, 571-574
  DVDs, 594
LAN setting (BIOS Onboard Devices menu), 316
LANs (local area networks), 854
Larson, Earl R., 10
Laser Beam Recorder (LBR), 572
lasers (CD drives), 573
latency, 365, 541-542
Layer Jump Recording (LJR), 609
layered architecture, 283-284
layout (memory), 356
lazy write, 779-780
LBA (logical block address)
  137 GB barrier and beyond, 466-468
  CHS/LBA conversions, 453-454
  compared to CHS (cylinder head sector), 452-453
  LBA-assist translation, 462-464
LBR (Laser Beam Recorder), 572
LCC (leadless chip carrier), 85
LCD (liquid crystal display)
  active-matrix displays, 717-718
  advantages of, 718
  bad pixels, 730
  dead pixels, 730
  how it works, 716-717
  lack of screen flicker, 714-715
  projectors, 721-722
  selection criteria, 718-719
  stuck pixels, 730
L-CHS parameters, 458
lead-in area
  CDs, 575
  DVDs, 595
lead-out area
  CDs, 575
  DVDs, 595
leadless chip carrier (LCC), 85
leased lines, 845-846
LED connectors, 253
LED monitors, 714-715
legacy support
  audio, 740
  ports, 757, 1002
  power management, 968
  USB, 805
legal issues
  copyright protection, 24
  licensing
    Mac OS X, 25
    MS-DOS, 25
    patents, 24
  Lell, Jakob, 775
  Lenovo POST display error codes, 1052-1053
  Level 1 cache, 360
    cache operation, 59-60
    importance of, 59
    Pentium-MMX improvements, 67
  Level 2 cache, 61-63, 360
  Level 3 cache, 61-62, 361
  level-sensitive interrupts, 275
  levels (RAID), 472-474
Lexar
  Memory Stick PRO, 552
  Memory Stick PRO Duo, 552
Lexmark, 803
LFX12V power supply, 922
licensing
  Mac OS X, 25
  MS-DOS, 25
LIF (low insertion force)
  sockets, 84
Light Peak (Thunderbolt technology), 782-784
LightScribe, 649
line conditioner, 985
line in sound card connectors, 741
line out sound card connectors, 741
line print terminal (LPT) ports, 789
line regulation (power supply), 958
linear power supply, 953-954
linear voice-coil actuators, 527
Lineo, 25
Link Layer Topology Discoverer (LLTD), 901
Link-5 transceiver (HP), 829
Linux
  ALSA (advanced Linux sound architecture), 748
  drive limitations, 469
  liquid cooling, 158-159, 1006
  lithium coin cell batteries, 1068
Live Update 6, 296
LJR (Layer Jump Recording), 609
Llano core, 137
L.I.F. See low-level formatting
LLTD (Link Layer Topology Discoverer), 901
Load Custom Defaults setting (BIOS Exit menu), 346
Load Optimal Defaults setting (BIOS Exit menu), 346
loading mechanisms (CD/DVD drives), 647
load/unload head mechanism, 505
loads (power supply), 953-954
  apparent power, 959
  inductive, 958
  load regulation, 958
  maximum load current, 958
  minimum load current, 958
  nonlinear, 959
  reactive power, 959
  resistive, 958
  working power, 959
local area networks (LANs), 854
local buses, 263-264
  PCI. See PCI buses
  VESA local bus, 264
locked systems, troubleshooting, 1095-1099
logic boards, 535-536
logic probes, 1071
logical block address. See LBA (logical block address)
logical formatting, 515-516, 520
logical memory layout, 356, 405-408
logical ring topology, 882
Logitech mice, 814
  iFeel mouse, 816
  Ultrathin Touch Mouse, 820
Long Duration Power Limit Override (Watts) setting (BIOS Performance menu), 333
Long Duration Power Limit Time Window setting (BIOS Performance menu), 334
long term evolution (LTE), 840-841
loopback connector, 1069-1070
low insertion force (LIF) sockets, 84
Mean Time To Failure (MTTF)

Index

1133

low profile form factor
(LFX12V) power supply, 922
low volume, troubleshooting, 750
low-level formatting (LLF), 515-516
standard recording, 516
ZBR (zoned-bit recording), 516-518
low-pass filters, 837
LPT (line print terminal) ports, 789
LPX motherboards, 170-172, 929-931
LTE (long term evolution), 840-841
lubricants, 1078
LVDS Spread Spectrum Control setting (BIOS Advanced Flat Panel Display menu), 326

M
M.2 (PCI Express), 438-439
MAC addresses, 869
Mac OS X HFS (Hierarchical File System), 633
licensing, 25
running on PCs, 26
Macrovision SafeAudio, 636
MagicGate Memory Stick, 552
magnetic fields, 477-478
magnetic flux, 478
magnetic storage
areal density, 492-494
bit cells, 478
capacity measurements, 491-492
disk/tape material, 477
electromagnetism, 476
encoding schemes, 478
comparison of, 489-490
explained, 486-487
FM (frequency modulation), 487
MFM (Modified Frequency Modulation), 487
RLL (run length limited), 488-489
flux, 478
head sliders, 483-486
heads, 476, 479-481
ferrite, 480
GMR (giant magneto-resistive), 482-483
MIG (Metal-In-Gap), 480
MR (magneto-resistive), 481-482
TF (thin film), 480
helium-filled drives, 497
history of, 475
magnetic fields, 477-478
overview, 475
PMR (perpendicular magnetic recording), 495-497
PRML (partial-response, maximum-likelihood) decoders, 490-491
read process, 478-479
SMR (Shingled Magnetic Recording), 497-498
write process, 478-479
magneto-resistive (MR) heads, 481-482
main boards. See motherboards
main memory. See RAM (random access memory)
main menu (BIOS Setup), 313-315
Maintenance menu (BIOS Setup), 311-312
maintenance. See care and maintenance
Make codes, 807
managed switches, 883
MANS (metropolitan area networks), 854
Mantle (AMD), 703-704
manufacturer-supplied diagnostic software, 1039
manufacturing
CDs, 571-573
manufacturing tests, 349
processors bonding, 77
dies, 76
doping, 75
metallization layers, 76
photolithography, 75-76
process, 77
process/wafer size transitions, 77-79
silicon, 74
silicon on insulator (SOI), 76
steppers, 76
test process, 77
wafers, 75-77
yields, 77
mapping
MIP mapping, 699
texture mapping, 699
mask ROM (read-only memory), 288
maskable interrupts, 272
mass-producing CDs, 571-573
master development (CDs), 572
master drives (ATA), 426
Master Key Hard Disk Drive Password setting (BIOS Security menu), 335
master position (ATA), 417
master separation (CDs), 572
Masuoka, Fujio, 548
Material Safety Data Sheets (MSDS), 1079
math coprocessors, 94, 102
matrix math extensions (MMX), 67-68
Mauchly, John W., 6, 10, 22
Max Inverter Current Limit (%) setting (BIOS Advanced Flat Panel Display menu), 326
Maximum Duty Cycle setting (BIOS Fan Control & Real-Time Monitoring menu), 328
maximum load current (power supply), 958
Maximum Non-Turbo Ratio setting (BIOS Performance menu), 333
MBR boot error messages, 352-353
MCA (MicroChannel Architecture) buses, 262, 273
MCH (Memory Controller Hub), 199, 1000
MCM (multichip module), 103
Mean Time Between Failures (MTBF), 543, 957
Mean Time To Failure (MTTF), 957
Minimum Temperature (°C) setting (BIOS Fan Control & Real-Time Monitoring menu), 328
mini-SATA (mSATA), 437
mini-tower cases, 997
Mini-Winchester sliders, 484
MiniSD, 552
MIO (multipurpose I/O), 704
mirroring disks, 472-473
misses (cache), 360
Missing operating system (error message), 353, 1096
MITS, Inc., 15, 22
MLC (multilevel cell), 555-556
MMC (MultiMediaCard), 551
MMCA (MultiMediaCard Association), 551
MMDevice (Multimedia Devices) API, 737
MMX (multimedia extensions), 67-68
MMX/SSE instructions, 94
Model 5100 (IBM), 15
Model 5150 (IBM), 15
model numbers (Intel), 196
modems
asynchronous versus synchronous communications, 847
cable modems, 833-835 explained, 847
modes
PATA DMA (direct memory access) transfer modes, 429-430
PATA PIO (Programmed I/O) transfer modes, 429
processor modes, 49-50
IA-32e 64-bit extension mode, 52-54
IA-32 mode, 50-51
IA-32 virtual real mode, 51-52
real mode, 50
Modified Frequency Modulation (MFM) encoding, 487
modular cables, 981-982
modular power supplies, 1023
module testers, 400
modules (memory)
capacities, 380-381
DIMMs (dual inline memory modules), 376
168-pin SDRAM DIMM, 378
DDR DIMM, 378, 384
DDR2 DIMM, 378, 384
DDR3 DIMM, 379, 384
DDR4 DIMM, 384
purchasing, 396
SDR DIMMs, 383
dual rank, 376
ECC (error correcting code), 391-392
hard fails, 389
installation, 397-398
memory banks, 382, 387-388
module size/features, determining, 385-387
parity checking, 390-391
purchasing
DIMMs, 396
obsolete memory, 397
suppliers, 395-396
registered modules, 382
replacing with higher-capacity versions, 397
RIMMs (Rambus inline memory modules), 376, 380
SIMMs (single inline memory modules), 376
30-pin SIMM, 377
72-pin SIMM, 377
purchasing, 397
single rank, 376
soft errors, 389-390
speeds, 388
troubleshooting, 399-403
diagnostic software, 399-400
memory defect isolation procedures, 403-405
POST (Power On Self Test), 399
step-by-step process, 401-403
types of errors, 401
upgrading, 392-395
Molex Mini-Fit Jr. power connectors (ATX), 933-934
monitors. See also video adapters; video display interface
adjusting, 729
aspect ratio, 709-710
bad pixels, 730
care and maintenance, 728
choosing, 723-724
dead pixels, 730
display size, 707-708
horizontal frequency, 714
image brightness and contrast, 715
interlaced versus noninterlaced modes, 715
LCD (liquid crystal display)
active-matrix displays, 717-718
advantages of, 718
how it works, 716-717
lack of screen flicker, 714-715
projectors, 721-722
selection criteria, 718-719
LED, 714-715
multiple monitors
Dualview, 722-723
heterogeneous adapters, 723
homogeneous adapters, 723
overview, 722
overview, 31, 657, 707
pixels, 710-714
plasma displays, 720
repairing, 731-732
resolution, 708-709
stuck pixels, 730
testing, 726-729
touchscreens
interfacing, 719-720
setup, 720
technologies, 719
touchscreen technology, 826-827
troubleshooting, 730-732, 1092-1093
vertical frequency, 714
mono in connectors, 742
monophonic sound cards, 745
Moore, Gordon, 17, 33-34
Moore’s Law, 17
Morris, Robert, 8
MOSEFs (Metal Oxide Semiconductor Field Effect Transistors), 12-13
MOS Technologies 6502 processor, 36
motherboards. See also BIOS (basic input/output system); buses; chipsets; PSUs (power supply units)
AT, 929-931
ATX, 178
color coding, 182
identifying, 180
ports, 181
power supply, 910-913
specification, 182
Baby-AT, 169-170
BTX, 174-177
cables, 1026-1027
connectors, 244-254
alternative single-row front panel connector pinouts, 248
AMR (Audio Modem Riser), 256
ATAPI-style line-in connectors, 255
battery connector, 253
CD audio connectors, 254
chassis intrusion connectors, 254
CNR (Communications and Networking Riser), 256
front panel audio connector pinout, 252-253
front panel switch/LED connector pinouts, 246-247
IEEE 1394a connector pinout, 252
infrared data front panel connector pinout, 253
LED and keylock connectors, 253
microprocessor fan power connectors, 255
power LED indications, 247-248
speaker connectors, 254
telephony connectors, 254
USB 1.1-2.0 header connector pinout, 249
USB 3.0 header connector pinout, 251
Wake on LAN connectors, 254
Desktop Form Factors website, 999
documentation, 279-280
DTX motherboards, 186
explained, 31, 999
extended ATX, 182
FlexATX, 184-186
full-size AT, 167-168
industry control of, 26
integrated adapters, 1002
ITX, 187-189
LPX, 170-172, 929-931
memory
DIMMs (dual inline memory modules), 1001
installation, 1017
microATX, 183-184
Mini-ATX, 179
Mini-DTX, 186
Mini-ITX, 187-189
mounting in case, 1018-1021
NLX, 172-173
PC motherboards, 166-167
ports, 1001-1003
processor sockets/slots, 189-192
proprietary designs, 189
PS/2 mouse port, 817
selection criteria, 278-279
summary of form factors, 165-166
Super I/O chips, 244
troubleshooting, 1099
UEFI (Unified Extensible Firmware Interface), 1001
voltage regulators, 905
WTX, 173
XT, 166-167
Mothers (CD), 572
Motion Pictures Experts Group (MPEG) standard, 747
motors
spindle motors, 534-535
stepper motors, 526
Mount Rainier standard, 621, 633-634
mounting motherboards, 1018-1021
mouse devices. See mice
Mouser Electronics, 1064
MOVs (metal-oxide varistors), 984
MPEG (Motion Pictures Experts Group) standard, 747
MPEG-2 codecs, 628
MPEG-2 decoders, 628
MR (magneto-resistive) heads, 481-482
mSATA (mini-SATA), 437
mSATA Port setting (BIOS SATA Drives menu), 321
mSATA Port x Hot Plug Capability setting (BIOS SATA Drives menu), 322
MSAUs (multistation access units), 882
MS-DOS. See DOS
MSDOS.SYS file, 1061
MSDS (Material Safety Data Sheets), 1079
msinfo32.exe, 515
MTBF (Mean Time Between Failures), 543, 957
MTTF (Mean Time To Failure), 957
MultiAudio, 592
multichip module (MCM), 103
multicore processors, 72
AMD 64 FX, 128-130
AMD Athlon 64 X2, 128-130
AMD Athlon X2, 128-130
AMD K10, 130-134
Intel Core 2, 112-115
Intel Core i, 116
Haswell architecture, 120, 152
Intel Atom, 121
Ivy Bridge architecture, 119
Nehalem architecture, 116-118
overclocking, 151
Sandy Bridge architecture, 118-119
Intel Pentium D, 110-113
Pentium Extreme Edition, 110-113
multidomain vertical alignment (MVA), 718
multiformat rewritable DVD drives, 612-613
multilevel cell (MLC), 555-556
MultiMediaCard Association (MMCA), 551
MultiMediaCard (MMC), 551
Multimedia CD, 593
Multimedia Devices
(MMDevice) API, 737
multimedia extensions (MMX), 67-68
multimeters, 1067, 1070-1071
MultiPlay specification, 592
multiple branch prediction, 69
multiple input, multiple output (MIMO), 865
multiple monitors, 722-723
Multiplier setting (BIOS Performance menu), 329
multipurpose I/O (MIO), 704
MultiRead specifications, 590-592
multisession recording (CDs)
DAO (disc-at-once) recording, 619
packet writing, 620-621
TAO (track-at-once), 620
multistation access units (MSAUs), 882
multithreaded rendering, 702
multi-touch digitizing pad, 1004
multi-touch integrated pad, 1004
multiword DMA (direct memory access), 430
municipal area networks (MANs), 854
music. See audio
MuTIOL architecture, 201
MVA (multidomain vertical alignment), 718
Mylar, 477

N
NAND (Not AND) flash memory, 548
Nano-ITX motherboards, 189
nanoseconds, 362
Napier, John, 5
Napier’s Bones, 5
National Committee on Information Technology Standards (NCITS), 412
National Institute for Standards and Technology (NIST), 451
National Television System Committee (NTSC), 695
Native ACPI OS PCIe Support setting (BIOS Power menu), 339
NCITS (National Committee on Information Technology Standards), 412
Near Field Communication (NFC), 854
NEAT (New Enhanced AT)
CS8221 chipset, 194
needle-nose pliers, 1067
negative DC voltages, 905-906
negative inertia, 824
Nehalem architecture (Core i), 116-118
Nero AG Software InCD Reader, 632
nested RAID levels, 472
NetBEUI, 893
NetBurst microarchitecture, 109
NET CONFIG SERVER command, 857
Network and Sharing Center, 901
network cards, 31, 292
network interface adapters, 1053
network interface cards. See NICs (network interface cards)
networks
ad hoc mode, 887
architecture summary, 858-860
benefits of, 854
Bluetooth, 868-869
broadband technology
CATV (cable TV), 832-836
cellular broadband, 840-841
comparison of access types, 846-847
DSL (digital subscriber line), 836-840
explained, 832
ISDN (Integrated Services Digital Network), 844-845
leased lines, 845-846
satellite broadband, 841-844
service interruptions, 849
status LEDs, 851-852
wireless broadband, 840
cables
cable distance limitations, 878-880
choosing, 899
grounding loops, 873
Thicknet, 871-872
Thinnet, 872
twisted-pair, 872-879
client/server networks, 856-858
defined, 31, 853-854
dialup modems, 847
eXtranets, 855
G.hn network standard, 895
HFC (hybrid fiber/coax) networks, 833
HomeGrid Forum, 895
HomePNA, 894-895
hubs, 884-885
infrastructure mode, 887
Internet, 855
intranets, 855
LANs (local area networks), 854
MANs (metropolitan area networks), 854
minimum requirements, 855
network software, 899-900
NICs (network interface cards), 292, 869-870
bus types, 870
connectors, 870-871
full-duplex, 870
half-duplex, 870
installation, 898
speed, 870
testing, 899
wireless NICs, 887-888
PANs (personal area networks), 854
peer-to-peer networks, 857-858
powerline networks, 895-896
security, 889-891
shared Internet connections, 850-851
switches, 883-884, 899
address storing, 884
compared to hubs, 884-885
dual-speed, 885
managed/unmanaged, 883
placement of, 886
ports, 885
power-saving features, 885
Index networks

topologies
  bus, 881-882
  explained, 880-881
  point-to-point, 889
  ring, 882-883
  star, 883, 888
WANs (wide area networks), 854
Wi-Fi (Wireless Fidelity)
  802.11a, 864-865
  802.11ac, 867
  802.11ad, 868
  802.11b, 863-864
  802.11g, 865
  802.11n, 865-867
  access points, 887, 899
  antennas, 888
  bridges, 888
  DHCP support, 891
  explained, 862-863, 888
  network speeds, 867
  repeaters, 888
  security, 889-891
  signal boosters, 888
  topologies, 889
  users per access point, 892
  wireless NICs, 887-888

wired Ethernet
  10 Gigabit Ethernet
  (10GBASE-T), 861-862
  cables. See cables explained, 859-860
  Fast Ethernet, 860-861
  Gigabit Ethernet, 861
  hubs, 884-885
  switches, 883-886, 899
WWANs (wireless wide area networks), 854

Neumann, John von, 6, 11
Newark/element14, 1064
Newegg.com, 999
New Enhanced AT (NEAT) CS8221 chipset, 194
NexGen Nx586 processors, 121
Next Generation Form Factor (NGFF), 438
NFC Forum, 854
NFC (Near Field Communication), 854
nForce family chipsets, 243-244
NGFF (Next Generation Form Factor), 438

Nibble Mode memory, 365-366
nibble mode (parallel ports), 791

NICs (network interface cards)
  bus types, 870
  connectors, 870-871
  costs, 869-870
  full-duplex, 870
  half-duplex, 870
  installation, 898
  speed, 870
  testing, 899
  wireless NICs, 887-888

Nirsoft WirelessNetView, 1084
NIST (National Institute for Standards and Technology), 451
nits, 715

North Bridge chipsets, 197-199, 1000
Norton Ghost (Symantec), 546
no-tool cases, 1066
Novell, 25, 469
Noyce, Robert, 6, 14, 33-34
NRZI (Non Return to Zero Inverted), 760

OCCT, 1055
OEMs (original equipment manufacturers), 291, 998
Oersted, Hans Christian, 476
OFDM (orthogonal frequency division multiplexing), 865-866, 896
Off state (APM), 965
offline devices, 985
“On Computable Numbers” (Turing), 5
Onboard Devices menu (BIOS Setup), 315-317
Audio, 320
PCI/PCIe Add-in Slots, 319
USB, 317-319
one-time programmable (OTP) chips, 288
online systems, UPS (uninterruptible power supply), 986-988
onscreen messages (POST), 1042
Award BIOS/Phoenix FirstBIOS, 1044-1045
IBM BIOS, 1049-1051
open sound system (OSS) API, 748
OpenAL, 738
OpenAL Soft, 738
OpenGL, 670, 700-701
operating range (power supply), 957
operating system diagnostic software, 1040, 1053-1054
operating-system-independent boot process, 1056-1060, 1089-1090
opposite track path (OTP), 601
optical Drive Order setting (BIOS Boot menu), 342
optical drives, 1003-1004
optical mice, 815-817
optical SPDIF out sound card connectors, 742
optical storage
Blu-ray
- compared to DVD, 615
- drive speed, 644
- explained, 613
- movie playback on PCs, 628
- speed and read/write times, 614-615
- care and maintenance, 653-654
CD drives
- access times, 645
- bootable CDs, 652
- buffers/cache, 646
- CAV (constant angular velocity), 640
- CLV (constant linear velocity), 640-643
- data transfer rates, 640
- DMA and Ultra-DMA, 646
- drive sealing, 648
- firmware updates, 654-655
- history of, 570-571
- interfaces, 646-647
- laser operation, 573
- loading mechanisms, 647
- mechanical drive operation, 574-575
- Mount Rainier, 633-634
- MultiAudio, 592
- MultiPlay, 592
- MultiRead, 590-592
- self-cleaning lenses, 648
- table of drive speeds/transfer rates, 641
- troubleshooting, 649-652
CDs
- audio data information, 577-578
- Blue Book standard (CD EXTRA), 623
- bootable CDs, 649, 652
- burning, 648
- capacity, 570, 581-582
- care and handling, 571
- CD-DA, 618
- CD-R, 583-587
- CD-ROM, 618
- CD-RW, 583-584, 588-590
- CD TEXT, 579
- construction, 571
- copy protection, 581, 635-636
- DRM (digital rights management), 636
- DualDisc, 624-625
- EFM data encoding, 582-583
- explained, 570, 580, 586-588
- file systems, 628-633
- form factor, 570
- For Music Use Only discs, 635
- frames, 577-578
- history of, 570-571
- hub clamping area, 575
- Labelflash, 649
- lands, 573-574
- lead-in, 575
- lead-out, 575
- LightScribe, 649
- mass production, 571-573
- Mount Rainier, 633-634
- multisession recording, 619-621
- Orange Book, 618-619
- PCA (power calibration area), 575
- Photo CD, 621-622
- Picture CD, 622
- pits, 573-574
- PMA (power memory area), 575
- program area, 575
- read errors, 580-581
- ripping, 634-635
- sampling rates, 578
- Scarlet Book (SA-CD), 623-624
- sector modes/forms, 618
- sectors, 577-578
- subcode bytes, 578-579
- Super Video CDs, 623
- table of CD formats, 616-617
- technical parameters, 576-577
- tracks, 575
- White Book (Video CD), 622-623
DVD drives, 641-645
- access times, 645
- BD drive speed, 644
- buffers/cache, 646
- compatibility, 627
- DMA and Ultra-DMA, 646
- drive sealing, 648
- DVD Multi, 612-613
- firmware updates, 654-655
- interfaces, 646-647
- loading mechanisms, 647
- MultiAudio, 592
- MultiPlay, 592
- MultiRead, 590-592
- self-cleaning lenses, 648
- troubleshooting, 649-652
DVDs
- audio data information, 598-599
- bootable DVDs, 649
- capacity, 601-604
- construction, 593-595
- copy protection, 636-640
- data zone, 595
- DIVX (Digital Video Express), 627
orthogonal frequency division multiplexing (OFDM), 866, 896
OS ACPI C2 Report setting (BIOS Power menu), 339
OS ACPI C3 Report setting (BIOS Power menu), 339
OS/2 Warp, 469
Osborne, Adam, 7
OS (open sound system) API, 748
OSTA (Optical Storage Tecnology Association), 632-633
OSx86 Project, 19, 26
OTP (one-time programmable) chips, 288
OTP (opposite track path), 601
output ratings (power supply), 955-956
overburning CDs, 586
overclocking, 142
bus speeds and multipliers, 149
CPU voltage settings, 152
Haswell processors, 152
Ivy Bridge processors, 151
modern PC clocks, 145-147
pitfalls, 149-151
quartz crystals, 142-145
Sandy Bridge processors, 151
tips and guidelines, 147-148
unlocking cores, 148-149
Overclocking Assistant setting (BIOS Performance menu), 329
overheating. See heating/cooling issues
overloading power supply, 973
Overridden Host Clock Frequency setting (BIOS main menu), 314
Overridden Memory Speed setting (BIOS main menu), 314
Overridden Processor Speed setting (BIOS main menu), 314
Overridden Processor Turbo Speed setting (BIOS main menu), 314
Overrider enabled <0096>-Defaults loaded (error message), 1045
overrides
bus overrides, 330
memory overrides, 331-332
processor overrides, 332-334
Over-Temperature Threshold setting (BIOS Fan Control & Real-Time Monitoring menu), 328
Over-Voltage Threshold setting (BIOS Fan Control & Real-Time Monitoring menu), 328
overvoltage protection (power supply), 958
oxide media, 523

P

P8 power supply connectors, 929-931
P9 power supply connectors, 929-931
packaging processors
BBUL (bumpless build-up layer), 80
FC-PGA (flip-chip pin grid array), 79
PGA (pin grid array), 79-80
SEC (single edge contact), 80
SPGA (staggered pin grid array), 78
Packet Binary Convolutional Coding (PBCC-22), 865
packets
ATAPI (AT Attachment Packet Interface), 449
packet writing, 620-621
PAC (PCI/AGP Controller). See North Bridge chipsets
paged memory, 365-366
Page Mode memory, 365-366
paging, 365	pairing, 101, 868
PAL (Phase Alternate Line), 695
Panel Power-Down Delay Time (ms setting (BIOS Advanced Flat Panel Display menu), 326
Panel Power-On Delay Time (ms setting (BIOS Advanced Flat Panel Display menu), 326
| PanelLink, 683 |
| PANs (personal area networks), 854 |
| Paragon GPT Loader, 309, 471 paragraphs (ROM), 286 |
| Parallel ATA. See PATA (Parallel ATA) |
| Parallel Port Mode setting (BIOS Onboard Devices menu), 317 |
| Parallel Port setting (BIOS Onboard Devices menu), 316 |
| Parallel ports 25-pin connectors, 789 bidirectional (8-bit), 791-792 compared to serial ports, 757-758 configuration, 792-793 ECP (Enhanced Capabilities), 792 EPP (Enhanced Parallel Port), 792 explained, 784, 789 IEEE 1284 standard, 790-791 standard, 791 parallel track path (PTP), 601 parameter translation. See translation PARD (Periodic and Random Deviation), 958 parity block data with, 472 checking, 390-391 errors, 401 parity bits, 390 parity inner (PI) bytes, 598 parity outer (PO) bytes, 598 striping with, 472 Parkinson, Cyril Northcote, 499 Parkinson’s Law, 499-500 Parted Magic, 515, 520 Partial-CAV (P-CAV) technology, 640 partial-response, maximum-likelihood (PRML) decoders, 490-491 PARTIES (Protected Area Run Time Interface Extension Services), 305 partitions GPT (GUID Partition Table), 470-471 HDDs (hard disk drives), 513-515, 519-520 SSD (solid-state drive), 557 parts grabbers, 1065, 1075 Pascal, Blaise, 5 Pascaline digital adding machine, 5 passive heatsinks, 156 passive PFC (power factor correction), 959 passive preventative maintenance, 1075 dust, 1085 heating and cooling, 1081-1082 operating environment, 1081 pollutants, 1085 power cycling, 1082 power-line noise, 1083-1084 RFI (radio-frequency interference), 1084 static electricity, 1083 PassMark Software, 334 passwords, 334 PATA (Parallel ATA), 412 defined, 409 DMA (direct memory access) transfer modes, 429-430 dual-drive configurations, 426-429 I/O cables, 423-425 I/O connectors, 419-422 40-pin connectors, 420-421 50-pin connectors, 422-423 PIO (Programmed I/O) transfer modes, 429 signals, 425-426 patents, 24 PAVP setting (BIOS Video menu), 325 PBCC-22 (Packet Binary Convolutional Coding), 865 PC 99 Design Guide website, 741 PC Advanced Technology (PC-AT), 7 PC133 specification, 367-368 PCA (power calibration area), 575 PC-AT (PC Advanced Technology), 7 P-CAV (Partial-CAV) technology, 640 PC Card, 553 Pc-Check, 1055 PC Diag Professional Suite, 1055 PC-Doctor Service Center, 1055 PCG (Platform Compatibility Guide), 940-941 PCH Core setting (BIOS Performance menu), 330 PCH Core Voltage Override setting (BIOS Performance menu), 330 PCH (Platform Controller Hub), 999 P-CHS parameters, 458 PCI (Peripheral Connect Interface), 265-268 adapter cards, 266 board configurations, 266-267 bus types, 266 interrupts, 275 IRQ Steering, 272, 275 PCI Express, 268-270 specifications, 264-265 PCI Bus Frequency setting (BIOS Performance menu), 330 PCI Bus Limit setting (BIOS Onboard Devices menu), 317 PCI buses, 256 PCI Express. See PCIe PCI Express Bus Frequency setting (BIOS Performance menu), 330 PCI Latency Timer setting (BIOS Onboard Devices menu), 316 PCI/PCIe Add-in Slots menu (BIOS Setup), 319 PCIe ASPM L0s setting (BIOS Power menu), 339 PCIe ASPM L1 setting (BIOS Power menu), 339 PCIe ASPM Support setting (BIOS Power menu), 339 PCIe (PCI Express), 256, 268-270, 679 lanes, 706-707 PCIe x16 Graphics Power connectors, 949-953 PCIe x16 v2.0, 86 PCIe x16 video cards, 1100 PCI Express M.2, 438-439
PCI/PCIe Slot Information setting (BIOS PCI/PCIe Add-in Slots menu), 319

PCMark benchmark, 57

PCMCIA (Personal Computer Memory Card International Association), 553

PC-Technician, 1055

PdaNet, 849

peak inrush current (power supply), 957

peer-to-peer networks, 857-858

Pentium, 100-102

BTB (branch target buffer), 101

chipsets, 202-203

instruction processing, 102

math coprocessor, 102

MMX (multimedia extensions), 67-68

socket specifications, 80-83

specifications, 101

SPGA (staggered pin grid array), 78

SSE (Streaming SIMD Extensions), 68

twin data pipelines, 100

Pentium II, 103-106

chipsets, 203-207

dynamic execution, 69-70

SECC (single edge contact cartridge), 80

socket specifications, 80-83

Pentium III, 103, 106-107

chipsets, 203-207

SECC (single edge contact cartridge), 80

socket specifications, 80-83

SSE (Streaming SIMD Extensions), 68

Pentium 4, 108-109

chipsets

ATI, 231

Intel 96x series, 217

Intel 915 family, 215

Intel 925X family, 215-216

Intel 945 Express family, 216

Intel 955X, 217

Intel 975X, 217

NVIDIA, 232

reference tables, 208-214

SIS, 231

ULI, 231

VIA, 232

NetBurst microarchitecture, 109

Pentium 4 Extreme Edition, 110

specifications, 109

Pentium-compatible processors

AMD Athlon, 122-123

AMD Athlon MP, 124

AMD Athlon XP, 124

AMD Duron, 123

AMD K6, 69, 122

AMD K6-2, 122

AMD Sempron, 128

NexGen Nx586, 121

Pentium D, 110-113, 231

Pentium Extreme Edition, 110-113

Pentium-MMX, 67-68

Pentium Pro, 103-104

chipsets, 203-207

dynamic execution, 69-70

socket specifications, 80-83

SPGA (staggered pin grid array) packaging, 78

Performance Memory Profiles setting (BIOS Performance menu), 331

Performance menu (BIOS Setup), 328-330

Bus Overrides, 330

Memory Overrides, 331-332

Processor Overrides, 332-334

performance optimization. See also heating/cooling issues

BD drives, 644

CD drives

access times, 645

buffers/cache, 646

CAV (constant angular velocity), 640

CLV (constant linear velocity), 640-643

data transfer rates, 640

drive speeds/transfer rates, 641

DVD drives, 641-645

access times, 645

buffers/cache, 646

DMA and Ultra-DMA, 646

HDDs (hard disk drives)

average access times, 542

average seek times, 541

cache programs, 542

interleave, 543

latency, 541-542

reliability, 543-546

transfer rates, 539-541

memory speed

clock speeds, 363

cycle times, 363

DDR SDRAM, 369-370

DDR2 SDRAM, 371-372

DDR3 SDRAM, 373-374

DDR4 SDRAM, 375

GHz (gigahertz), 362

interleaving, 366

MHz (megahertz), 362

module speeds, 388

nanoseconds, 362

processor bus speeds, 363-365

SDRAM, 368

overclocking

bus speeds and multipliers, 149

CPU voltage settings, 152

IHaswell processors, 152

Ivy Bridge processors, 151

modern PC clocks, 145-147

pitfalls, 149-151

quartz crystals, 142-145

Sandy Bridge processors, 151

tips and guidelines, 147-148

unlocking cores, 148-149

software, 700

Periodic and Random Deviation (PARD), 958

Peripheral Connect Interface buses. See PCI buses

peripheral diagnostics software, 1040

peripheral power connectors, 946-947

peripherals. See input devices

perpendicular magnetic recording (PMR), 495-497

personal area networks (PANs), 854

Personal Computer Memory Card International Association, 553

perspective correction, 699

PFA (Predictive Failure Analysis), 544

PFC (power factor correction), 958-959

PGA (pin grid array), 79-80
Phase Alternate Line (PAL), 695
phase-change material, 157
phase-change recording, 607
Phenom
chipsets
AMD 690 series chipsets, 236
AMD 700 series chipsets, 237-238
AMD 800 series chipsets, 237-238
AMD 900 series chipsets, 237-241
AMD A series chipsets, 241-243
AMD (ATI) 480x and 500 series chipsets, 236
overview, 130-134
Phenom II, 130-134
Philips CD-ROM design, 570-571
Phoenix Technologies
BIOS error codes, 352
Phoenix BIOS 4 and later, 1048
Phoenix BIOS 486 and earlier, 1046-1047
POST error codes, 1043-1044
POST onscreen messages, 1044-1045
reverse engineering of IBM software, 24-25
phone line surge protectors, 984-985
Photo CDs, 621-622
photolithography, 75-76
photoresist coating (CDs), 572
physical configuration, documenting, 1010
physical formatting. See low-level formatting
PI (parity inner) bytes, 598
Pico-ITX motherboards, 189
pico sliders, 507
piconets, 868
Picture CDs, 622
piezoelectricity, 142-143
Piledriver FX processors, 134-137
pin grid array (PGA), 79-80
pinned magnetic layers, 483
PIO (Programmed I/O) transfer modes, 429
pitch, 734
pits
CDs, 571-574
DVDs, 594
pixels, 710-714
bad pixels, 730
dead pixels, 730
pixels per inch (PPI), 815
stuck pixels, 730
pixie dust, 524
planar. See motherboards
plasma displays, 720
plated thin-film media, 523
Platform Compatibility Guide (PCG), 940-941
Platform Controller Hub (PHC), 999
Platform Key (PKpub) setting (BIOS Secure Boot Configuration menu), 345
platters, 504, 522
pliers, 1067
Plug and Play. See PnP
PMA (power memory area), 575
PMOS transistors, 13
PMR (perpendicular magnetic recording), 495-497
PnP (Plug and Play) hot-plugging, 767
PnP BIOS, 347-348
PO (parity outer) bytes, 598
POD (Pseudo Open Drain), 374, 675
point of presence (PoP), 845
point-to-point topology, 889
pointing devices choosing, 1004
mice
ball-driven mice, 815
buttons, 815
cleaning, 821, 1080-1081
components, 814-815
defined, 31
history of, 814
hybrid mice, 818-819
keyboard/mouse interface connectors, 808-809
manufacturers, 814
optical mice, 815-817
PS/2 mouse port, 817
scroll wheels, 819
touch-sensitive mice, 820
troubleshooting, 821
USB (Universal Serial Bus), 818
pointing sticks, 822
touch pads, 824-825
touchscreen technology, 826-827
trackballs, 814, 825-826
TrackPoint, 822-824
touch-sensitive mice, 820
troubleshooting, 821
wireless, 827
Bluetooth, 828
IR (infrared), 828
multiple devices with single tranciever, 829
power management, 828-829
proprietary radio frequency, 828
troubleshooting, 829
polarizing filters (LCDs), 716-717
pollutants, 1085
PoP (point of presence), 845
Portable Device Charging Mode setting (BIOS USB menu), 318
ports
addresses, 276-277
ATX motherboard ports, 181
EUHP (eSATA USB Hybrid Port), 441
explained, 757, 1001-1003
FireWire. See FireWire
hot-plugging, 779-782
IEEE 1394. See IEEE, IEEE 1394
legacy ports, 757, 1002
motherboard mouse port (PS/2), 817
parallel ports
25-pin parallel port connectors, 789
bidirectional (8-bit) parallel ports, 791-792
compared to serial ports, 757-758
configuration, 792-793
ECP (Enhanced Capabilities) parallel ports, 792
EPP (Enhanced Parallel Port), 792
explained, 784, 789
IEEE 1284 standard, 790-791
standard parallel ports, 791
serial ports
9-pin serial port connectors, 787
9-pin-to-25-pin serial port connectors, 788
25-pin serial port connectors, 787
compared to parallel ports, 757-758
configuration, 788
explained, 784-785
locations, 785-788
UART (Universal Asynchronous Receiver/Transmitter) chips, 788
switch ports, 885
USB. See USB (Universal Serial Bus)

positive DC voltages
voltage rails, 904-905
voltage regulators, 905

positive-pressure-ventilation design, 912
POS (Power on Suspend), 971
POST (power on self test)
audio error codes, 1041
AMI BIOS, 1042-1043
Award BIOS/Phoenix FirstBIOS, 1043-1044
IBM BIOS, 1048
IBM/Lenovo, 1052-1053
Phoenix BIOS, 1046-1048
checkpoint codes, 1041
explained, 285, 399, 1039-1040
fatal errors, 1040
onscreen messages, 1042
Award BIOS/Phoenix FirstBIOS, 1044-1045
IBM BIOS, 1049-1051
POST cards, 1067
troubleshooting, 1089-1090
POST Code Routing setting (BIOS Boot Display Options menu), 344
postcodemaster.com, 1041
Poulsen, Valdemar, 495
power calibration area (PCA), 575
power connectors
4-pin +12V power connectors, 941-942
4-pin to 8-pin +12V power connectors, 944
8-pin +12V power connectors, 942-943
AT, 929-931
ATX12V 2.x 24-pin, 936-939
ATX/ATX12V 1.1
6-pin auxiliary power connectors, 935-936
20-pin main power connectors, 931-933
maximum power-handling capabilities, 934-935
Molex Mini-Fit Jr. power connectors, 933-934
backward/forward compatibility, 944-946
Dell proprietary ATX design, 946
explained, 928-929
floppy power connectors, 947-948
PCG (Platform Compatibility Guide), 940-941
PCI Express x16 Graphics Power connectors, 949-953
peripheral power connectors, 946-947
power switch connectors
color coding, 927-928
front panel motherboard-controlled switches, 925-927
front panel power supply AC switches, 927-928
integral power supply AC switches, 927
SATA power connectors, 948-949
VRM (voltage regulator module), 939-940
power cycling, 968-971, 1082
Power Delivery (USB), 773
power factor correction (PFC), 958-959
Power_Good signal, 906-907
power LED indications, 247-248
power management. See also PSUs (power supply units)
80 PLUS Program, 963-964
ACPI (Advanced Configuration and Power Interface), 966-968
APM (Advanced Power Management), 965
BIOS Power menu, 337-340
DPMS (Display Power Management Signaling), 716
Energy 2000 standard, 716
Energy Star standard, 716
ENERGY STAR systems, 965
game legacy power management, 968
SMM (System Management Mode), 65-66
wireless input devices, 828-829

power memory area (PMA), 575
Power menu (BIOS Setup), 337-340
Power_OK signal, 906-907
power on self test. See POST (power on self test)
Power on Suspend (POS), 971
Power Over eSATA (eSATAp), 441-443
Power Supervisor Shutdown setting (BIOS Power menu), 339
Power Supply Design Guide for Desktop Platform Form Factors, 942
power supply. See PSUs (power supply units)
power supply testers, 977-978
power switch connectors
color coding, 927-928
front panel motherboard-controlled switches, 925-927
front panel power supply AC switches, 927-928
integral power supply AC switches, 927
Power-On to Backlight Enable setting (BIOS Advanced Flat Panel Display menu), 326

energy positive-temperature coefficient (PTC) thermistors, 902
power-line noise, 1083-1084
PSUs (power supply units)

Index

1145

power-protection systems

backup power

standby power supply, 985-986

UPS (uninterruptible power supply), 986-988

explained, 982-984

line conditioners, 985

phone line surge protectors, 984-985

surge protectors, 984

powerline networks, 895-896

PPI (pixels per inch), 815

PrairieTek 2.5" drives, 502-503

preboot environment (BIOS), 305-307

Predictive Failure Analysis (PFA), 544

prefetching, 68

prefixes for decimal/binary multiples, 451

pre-grooves (CD-R), 584

Press ESC to skip memory test (error message), 1044

Press TAB to show POST screen (error message), 1045

preventative maintenance. See care and maintenance

Primary master hard disk fail (error message), 1045

Primary slave hard disk fail (error message), 1045

Primary Video Adapter setting (BIOS Video menu), 325

primitives, 699

PRML (partial-response, maximum-likelihood) decoders, 490-491

probes (logic), 1071

Processor C States setting (BIOS Power menu), 339

Processor Core setting (BIOS Performance menu), 310

processor ducts, 161

Processor Frequency ID Utility, 148

Processor Identification Utility, 148

Processor Overrides settings (BIOS Setup), 332-334

Processor Power Efficiency Policy setting (BIOS Power menu), 340

Processor Speed setting (BIOS main menu), 314

Processor System Agent setting (BIOS Performance menu), 330

Processor Turbo Speed setting (BIOS main menu), 314

Processor Type setting (BIOS main menu), 314

processors. See specific processors (for example, Pentium)

Professional 3DNow!, 69

program area (CDs), 575

programmable ROM (PROM), 288-289

Programmed I/O (PIO) modes, 429

projectors, LCD (liquid crystal display), 721-722

PROM (programmable ROM), 288-289

proprietary-design motherboards, 189

proprietary power supply standards, 909

proprietary radio frequency input devices, 828

ProtectDisc, 638

Protected Area Run Time Interface Extension Services (PARTIES), 305

protective coating (CDs), 573

PS/2 mouse port, 817

PS/2 Port setting (BIOS Onboard Devices menu), 317

PS/2-type connectors, 169

PS3 form factor, 914

PSB (processor side bus). See buses

Pseudo Open Drain (POD), 374, 675

PS_ON signal, 906, 925

PSUs (power supply units)

battery

replacing, 992

RTC/NVRAM, 988-992

buying tips, 980-982

connecting, 1023-1025

constant voltage, 903

CrossfireX certification, 960
defined, 31

efficiency, 958

ESD (electrostatic discharge) protection, 1009-1010, 1068

floppy power connectors, 947-948

form factors

ATX/ATX12V, 910-913

CFX12V, 920

EPS/EPS12V, 917-918

explained, 907-908

Flex ATX, 922-924

LFX12V, 922

proprietary standards, 909

PS3, 914

SFX/SFX12V, 913-917

table of, 909

TFX12V, 918-920

hold-up time, 957

importance of, 903

input range, 957

linear design, 953-954

line regulation, 958

loads, 953-954

apparent power, 959

inductive, 958

load regulation, 958

maximum load current, 958

minimum load current, 958

reactive power, 959

resistive, 958

working power, 959

modular cables, 981-982

modular power supplies, 1023

motherboard power connectors

4-pin +12V power connectors, 941-942

4-pin to 8-pin +12V power connectors, 944

8-pin +12V power connectors, 942-943

AT, 929-931

ATX12V 2.x 24-pin, 936-939

ATX/ATX12V 1.x, 931-936
backward/forward, 944-946
Dell proprietary ATX design, 946
explained, 928-929
PCG (Platform Compatibility), 940-941
power switch connectors, 925-928
VRM (voltage regulator), 939-940
MTBF (Mean Time Between Failures), 957
negative DC voltages, 905-906
output ratings, 955-956
overloading, 973
overvoltage protection, 958
PARD (Periodic and Random Deviation), 958
PCI Express x16 Graphics Power connectors, 949-953
peak inrush current, 957
peripheral power connectors, 946-947
PFC (power factor correction), 958-959
positive DC voltages
  voltage rails, 904-905
  voltage regulators, 905
power cycling, 968-971
power management, 716, 968
  80 PLUS Program, 963-964
ACPI (Advanced Configuration and,
  966-968
APM (Advanced Power Management), 965
DPMS (Display Power Management Signaling), 716
Energy 2000 standard, 716
ENERGY STAR systems, 965
SMM (System Management Mode), 65-66
Power_Good signal, 906-907
power-protection systems
  backup power, 985
explained, 982-984
line conditioners, 985
phone line surge protectors, 984-985
surge protectors, 984
power-use calculations, 961-963
powering off/on
  electrical costs, 969-970
  S3 (Suspend To RAM) state, 970-971
  S4 (Hibernate) state, 971
  thermal shock, 968-969
preventative maintenance
  power cycling, 1082
  power-line noise, 1083-1084
  static electricity, 1083
processor operating voltages, 93-94, 152
protective features, 956
ripple, 958
safety certifications, 960-961
SATA power connectors, 948-949
SLI-ready, 960
soft-power feature, 906
sources for replacement power supplies, 982
switching design, 904, 953-954
test equipment
  back probing, 976-977
  digital infrared
  thermometers, 979
  DMMs (digital multimeters), 974-977
  power supply testers, 977-978
  variable voltage transformers, 979-980
  transient response, 957
  troubleshooting, 972-973, 1090
diagnostic procedures, 973
  inadequate cooling, 973-974
  overloaded power supply, 973
universal power supplies, 956
voltage measurements, 976-977
PTP (parallel track path), 601
P-type silicon, 12
pure mechanical keyswitches, 798-800
PWR_OK signal, 906-907
QPI Power Management setting
  (BIOS Power menu), 340
QPI (Quick Path Interconnect), 87
QPSK/CCK data encoding, 865
QuantiSpeed, 124
quartz crystals, 142-145
Quick Path Interconnect (QPI), 87
QuickStop response
  (TrackPoint), 824
QuickTechPRO, 1055
quiet boots, 293
RAB (Raid Advisory Board), 472
Radio-Electronics, 866
radio frequency input devices, 828
radio-frequency interference (RFI), 1084
RadioLabs, 1085
Raid Advisory Board (RAB), 472
RAID (redundant array of independent disks), 471
  levels, 472-474
  onboard BIOS, 292
  software RAID, 474
rails (voltage), 904-905
RAMAC (Random Access Method of Accounting and Control), 475
Rambus DRAM (RDRAM), 375
Rambus inline memory modules (RIMMs), 376, 380
RAM (random access memory)
  cache, 1001
    bus snooping, 65
    cache controllers, 65
defined, 58, 360
direct-mapped cache, 64
explained, 359
fully associative mapped cache, 64
hard disk drive cache programs, 542
hits/misses, 360
Level 1, 58-60
Level 2, 61
Level 3, 61-62
Pentium-MMX improvements, 67
performance and design, 62-63
set associative cache, 64
speed, 65
TLB (translation lookaside buffer), 65
write-back cache, 401
write-through cache, 64
CMOS RAM
addresses, 303-304
backing up, 294
configuring with BIOS Setup. See Setup (BIOS)
defined, 284-285
diagnostic status byte codes, 304
compared to storage, 356
DDR SDRAM, 368-370
DDDR2 SDRAM, 370-372
DDDR3 SDRAM, 372-374
DDDR4 SDRAM, 374-375
defined, 31
DIP (dual inline package) chips, 375
DMA (Direct Memory Access), 276, 646
DRAM (dynamic RAM), 357-359
ECC (error correcting code), 391-392
EDO RAM (extended data out RAM), 366-367
explained, 355-357
FPO DRAM (Fast Page Mode DRAM), 365-366
hard fails, 389
HMA (high memory area), 52
installation, 1017
layout, 356
logical mapping, 356
memory modules capacities, 380-381
DIMMs (dual inline memory modules), 376-379, 383-384, 396, 1001
dual rank, 376
installation, 397-398
memory banks, 382, 387-388
module size/features, 385-387
purchasing, 395-397
registered modules, 382
replacing with higher-capacity versions, 397
RIMMs (Rambus inline memory modules), 376, 380
SIMMs (single inline memory modules), 376-377, 397
single rank, 376
speeds, 388
parity checking, 390-391
purchasing, 395-397
RTC/NVRAM batteries, 988
modern CMOS batteries, 989-990
obsolete/unique CMOS batteries, 990-991
troubleshooting, 991-992
SDRAM (synchronous DRAM), 367-368
soft errors, 389-390
speed
clock speeds, 363
cycle times, 363
GHz (gigahertz), 362
interleaving, 366
MHz (megahertz), 362
nanoseconds, 362
processor bus speeds, 363-365
SRAM (static RAM), 359-361
system logical memory layout, 405-408
troubleshooting, 399-403, 1096-1099
diagnostic software, 399-400
memory defect isolation procedures, 403-405
POST (Power On Self Test), 399
step-by-step process, 401-403
types of errors, 401
Ultra-DMA, 646
upgrading, 392-395
video RAM, 674-675, 707
DDR SDRAM, 675
GDDR2 SDRAM, 675
GDDR3 SDRAM, 675
GDDR4 SDRAM, 676
GDDR5 SDRAM, 676
RAM calculations, 676-677
SGRAM, 675
speed, 676
video memory bus width, 677-678
VRAM, 675
WRAM, 675
volatile storage, 356
RAMdisk, 554
Random Access Method of Accounting and Control (RAMAC), 475
ranks of memory modules, 376
rasterization, 699
Raytek, 979
RDRAM (Rambus DRAM), 375
reactive power, 959
read errors (CDs), 580-581
read latency, 365
read-only memory. See ROM (read-only memory)
read process
flash memory, 563-564
magnetic storage, 478-479
read/write heads. See heads
ReadyBoost, 564-565
real mode, 50, 406
Realtek 3D SoundBack, 739
real-time clock/nonvolatile memory (RTC/NVRAM), 284
real-time clock. See RTC (real-time clock)
rear out sound card connectors, 742
receptacle testers, 1072
recording
CDs, 586, 648
DAO (disc-at-once) recording, 619
packet writing, 620-621
track-at-once, 620
recording media, 522
AFC (antiferromagnetically coupled), 523-524
oxide, 523
thin-film, 523
sound sampling, 735-736
standard recording, 516
ZBR (zoned-bit recording), 516-518
Recording Review, 748
Index

recovery
flash BIOS, 300-302
HDDs (hard disk drives), 505-506
System Restore, 1076
Recuva, 520
Red Book (CD-DA) format, 618
Red Hill Hardware Guide, 506
Reduced Instruction Set
Computer (RISC), 66, 795
redundant array of
independent disks. See RAID
refresh rates, 714
region codes (Blu-ray), 640
region-free DVD players, 639
regional playback control
(RPC), 639
The Register, 28
registered memory modules, 382
regulators (voltage), 905
reinstalling components, 1086
reliability
ATA (AT Attachment), 410
HDDs (hard disk drives)
MTBF (mean time between failures), 543
PFA (Predictive Failure Analysis), 544
S.M.A.R.T. (Self-Monitoring, Analysis, and Reporting Technology), 544-546
remote power switch
connectors. See power switch connectors
Removable Drive Order setting
(BIOS Boot menu), 342
removable storage devices
choosing, 1003-1004
explained, 547
flash memory
card capacities, 560-561
card readers, 563-564
CFast, 550
CompactFlash, 549-550
comparison of, 559-561
development of, 548
device sizes, 549
explained, 356, 547-549
file systems, 562-563
Flash-based SSDs, 554-555
keychain devices, 547
Lexar Memory Stick PRO, 552
Lexar Memory Stick PRO Duo, 552
MMC (MultiMediaCard), 551
NAND (Not AND), 548
NOR (Not OR), 548
PC Card, 553
ReadyBoost support, 564-565
SD (SecureDigital), 552
SmartMedia, 551
Sony Memory Stick, 552
Sony Memory Stick Micro, 552
Sony Memory Stick PRO-XC, 552
speed classes, 561-562
SSD (solid-state drive), 553, 557-558
thumb devices, 547
USB flash drives, 558-559
xD-Picture Card, 553
XQD, 550-551
floppy drives, 566-567
SSD (solid-state drive), 553
applications, 557-558
Flash-based SSDs, 554-555
MLC (multilevel cell), 555-556
partition alignment, 557
SLC (single-level cell), 555-556
SSD awareness in Windows, 556
TLC (triple-level-cell), 555-556
TRIM command, 556-557
virtual SSD (RAMdisk), 554
tape drives, 567
rendering images, 699-700
AMD CrossFire, 705-707
AMD Eyefinity, 706
NVIDIA SLI, 704-705
PCIe lanes, 706-707
video RAM size, 707
Repeat Delay parameter
(Windows keyboards), 806
Repeat Rate parameter
(Windows keyboards), 806
repeaters, wireless, 888
replacing components
batteries, 992
bootstrap approach, 1087-1088
compared to reinstalling
components, 1086
known-good spare technique, 1087
power supply, 982
video adapters, 1033
report status command, 544
reprogrammable microcode, 95
Reset Intel AMT to default
factory setting (BIOS
Maintenance menu), 312
resistive power, 958
resolution, 708-709
resources. See system resources
Responsiveness setting (BIOS
Fan Control & Real-Time
Monitoring menu), 328
Restore Default Configuration
setting (BIOS Fan Control &
Real-Time Monitoring menu), 328
restore points, 1076
Resuming from disk, Press TAB
to show POST screen (error
message), 1045
reverse-engineering
software, 24
RF (radio frequency) input
devices, 828
RFI (radio-frequency interference), 1084
RG-58 cable (Thinnet), 872
RIMMs (Rambus inline memory
modules), 376, 380
ring topology, 882-883
ripping CDs, 634-635
ripple (power supply), 958
RISC (Reduced Instruction Set
Computer), 66, 795
RJ-45 connectors, 870
RLL (run length limited), 488-489
Roberts, Ed, 15
Rock Ridge file system, 633
Rock Ridge Interchange
Protocol (RRIP), 633
ROM (read-only memory). See also BIOS (basic input/output
system)
defined, 285-286
EEPROM (electronically
erasable programmable
ROM), 290-291
EPROM (erasable programmable ROM), 289-290
explained, 357
flash ROM, 290-291
hardware, 285-287
manufacturers, 291
mask ROM, 288
PROM (programmable ROM), 288-289
shadowing, 287
root hubs, 760
rotary voice-coil actuators, 528
routers, 850-851
RPC (regional playback control), 639
RRIP (Rock Ridge Interchange Protocol), 633
RTC (real-time clock), 284, 988
modern CMOS batteries, 989-990
obsolete/unique CMOS batteries, 990-991
troubleshooting, 991-992
RTS2011LC cooling system, 159
rubber dome keyswitches, 801
run length limited (RLL), 488-489
Rutledge, Joseph, 822
SanDisk Corporation
CFast, 550
CompactFlash, 549-550
XQD, 550-551
Sandy Bridge architecture, 118-119, 151, 224-225
SAS (Shugart Associates System Interface). See SCSI (small computer system interface)
SATA Controller Mode setting (BIOS SATA Drives menu), 322
SATA Drives menu (BIOS Setup), 320-323
SATA Express, 432-434
SATA Port x setting (BIOS SATA Drives menu), 322
SATA (Serial ATA)
AHCI (Advanced Host Controller Interface), 444-445
backward compatibility, 431
BIOS Setup, 320-323, 443
cables and connectors, 434-437
CD/DVD drive interfaces, 646-647
defined, 409
eSATA (external SATA), 439-441
eSATAp (Power Over eSATA), 441-443
explained, 431
mSATA (mini-SATA), 437
NVMe (Non-Volatile Memory Express), 445
PCI Express M.2, 438-439
power connectors, 948-949
SATA Express, 432-434
Serial ATA International Organization, 412, 432
standards and performance, 431-432
transfer modes, 432, 445-446
scalable link interface (SLI), 949-953
scan codes, 806-807
scan conversion, 699
scan-line interfacing (SLI), 704
scan rates, 714
Scarlet Book standard (SA-CD), 623-624
SCAT (Single Chip AT) chipsets, 194
scientific method, 1086
scratchy sound, troubleshooting, 751-752
screwdrivers, 1067, 1074
scroll wheels (mouse), 819
SCSI (small computer system interface), 566
SD (SecureDigital), 552
SD (Super Density) disks, 593
SDP (serial presence detect), 383
SDRAM (synchronous DRAM), 367-368, 378
SDR (single data rate) DIMMs, 368, 383
SDSL (Symmetrical DSL), 838
Seagate 8TB Archive v2 HDD, 497
sealing CD/DVD drives, 648
SECAM (Sequential Couleur Avec Mémoire), 695
SECC (single edge contact cartridge), 80
SEC-DED (single-bit error-correction double-bit error detection), 391
second-party memory modules, 395
secondary cache. See Level 2 cache
Secondary LAN setting (BIOS Onboard Devices menu), 317
Secondary master hard disk fail (error message), 1045
Secondary SATA Mode setting (BIOS SATA Drives menu), 322
Secondary SATA setting (BIOS SATA Drives menu), 322
Secondary slave hard disk fail (error message), 1045
Secondary USB 3.0 Controller setting (BIOS USB menu), 318
sector addressing

- CHS (cylinder head sector)
  - 2.1 GB barrier, 459
  - 4.2 GB barrier, 460-462
  - 8.4 GB barrier, 465-466
  - 528 MB barrier, 455-457
- BIOS commands versus ATA commands, 454
- CHS bit-shift translation, 457-459
- CHS/LBA conversions, 453-454
- compared to LBA (logical block address), 452-453
- LBA (logical block address)
  - 137 GB barrier and beyond, 466-468
- BIOS commands versus ATA commands, 454
- CHS/LBA conversions, 453-454
- compared to CHS (cylinder head sector), 452-453
- LBA-assist translation, 462-464
- prefixes for decimal/binary multiples, 451

sectors, 504. See also sector addressing: tracks

- 512-byte sector in recent drives, 510
- Advanced Format (4K sectors), 511-513
- CDs, 577-578
- data bytes, 508
- defined, 507
- DVDs, 598-599
- fields, 508
- gaps in, 508
- headers/trailers, 508
- No-ID sector format, 509
- numbering, 508
- sector drive partition alignment, 513-515
- usable space, 508
- Western Digital WD1003/WD1006 (IBM AT) 512-byte sector format, 509
- Xebec 1210/1220 (IBM XT) 512-byte sector format, 509

Secure Boot setting (BIOS Secure Boot Configuration menu), 345

Secure Boot Mode setting (BIOS Secure Boot Configuration menu), 345

Secure Virtual Machine (SVM) Mode setting (BIOS Setup), 346

security

- ATA (AT Attachment)
  - ATA Security Mode, 447-448
  - HPAs (host protected areas), 448-449
- biometric security, 559
- BIOS Setup settings, 334-337
- CD copy protection, 581, 635-636
- CMS (content scramble system), 637-638
- ProtectDisc, 638
- region codes, 640
- RPC (regional playback control), 639
- Internet connections explained, 848-849
- routers, 850-851
- service interruptions, 849
- shared connections, 850
- passwords, 334
- power-protection systems explained, 848-849
- backup power, 985
- explained, 982-984
- line conditioners, 985
- phone line surge protectors, 984-985
- surge protectors, 984
- USB (Universal Serial Bus), 774-775
- viruses, 295
- war driving, 889
- WEP (wireless equivalent privacy), 890-891
- wireless networks, 889-891
- WPA (Wi-Fi Protected Access), 890
- Security menu (BIOS Setup), 334-337
- seek times, 500, 541
- Seidon 120 liquid cooler, 159
- self-cleaning lenses (CD/DVD drives), 648
- Self-Monitoring, Analysis, and Reporting Technology (S.M.A.R.T.), 415, 544-546
- Selker, Ted, 822
- semiconductors, 12, 28
- semiproprietary LPX motherboards, 170
- Sempron processors chips
- AMD 690 series, 236
- AMD 700 series, 237-238
- AMD 800 series, 237-238
- AMD 900 series, 237-241
- AMD A series, 241-243
- AMD (ATI) 480x and 500 series, 236
- overview, 128-134
- sensitivity of mice, 815
- SEPP (single edge processor package), 80
- Sequential Couleur Avec Mémoire (SECAM), 695
- Serial ATA International Organization, 412, 432
- Serial ATA. See SATA
- Serial Port Swap setting (BIOS Onboard Devices menu), 317
- Serial Port x setting (BIOS Onboard Devices menu), 317
- serial ports, 788
  - 9-pin serial port connectors, 787
  - 9-pin-to-25-pin serial port connectors, 788
  - 25-pin serial port connectors, 787
  - compared to parallel ports, 757-758
- configuration, 788
- explained, 784-785
- locations, 785-788
- UART (Universal Asynchronous Receiver/Transmitter) chips, 788

serial presence detect (SPD), 383

- Series A/B connectors (USB), 766
- SERS (soft error rates), 358, 389-390
servo mechanisms, 528-531
  dedicated servo, 531-532
disk sweep, 529
embedded servo, 530-531
gray code, 528
servowriters, 528
thermal recalibration, 529
wedge servo, 530
servo-controlled systems, 527
servowriters, 528
set associative cache, 64
Set Hard Disk Drive Password setting (BIOS Security menu), 335
Set Master Key Hard Disk Drive Password setting (BIOS Security menu), 335
SET MAX ADDRESS command, 449
Set Supervisor Password setting (BIOS Security menu), 336
Set User Password setting (BIOS Security menu), 336
Setup (BIOS), 285
  accessing, 310
  Advanced Flat Panel Display menu, 325-326
  AMD-specific BIOS settings, 346
  Audio menu, 320
  Boot Configuration menu, 344
  Boot—Boot Display Options menu, 343-344
  Boot—Secure Boot Configuration menu, 345
  Boot menu, 341-343
  Exit menu, 345-346
  Fan Control & Real-Time Monitoring menu, 327-328
  main menu, 313-315
  Maintenance menu, 311-312
  Onboard Devices menu, 315-317
  overview, 310-311
  PCI/PCIe Add-in Slots menu, 319
  Performance menu, 328-330
  Bus Overrides, 330
  Memory Overrides, 331-332
  Processor Overrides, 332-334
  Power menu, 337-340
  running, 1033-1035
SATA Drives menu, 320-323
  Security menu, 334-337
  USB menu, 317-319
  Video menu, 323-325
setup passwords, 334
SEUs (single event upsets), 389
SFX power supply, 913-917
SFX12V power supply, 913-917
SGI OpenGL, 700-701
SGRAM (Synchronous Graphics RAM), 657
shading, 697-699
shadowed ROM (read-only memory), 287
sharing
  Internet connections, 850-851
  interrupts, 272
shielded twisted-pair (STP) cables, 872-873
Shima, Masatoshi, 34-35
Shingled Magnetic Recording (SMR), 497-498
Shockley, William, 6, 12
Short Duration Power Limit Override (Watts) setting (BIOS Performance menu), 334
Shugart, Alan, 502, 566
Shugart Associates, 502
Shugart Associates System Interface (SASI). See SCSI (small computer system interface)
shutdown, troubleshooting, 1091
Shutdown.exe, 1063
signals
  keyboard connector signals, 809
  PATA (Parallel ATA) signals, 425-426
  Power_Good, 906-907
  PS_ON, 906, 925
  signal boosters, 888
  signal processing methods (audio), 743
  signal skew, 757
  signal-to-noise ratio (SNR), 735
SIIG, 452
silicon, 12, 74
  silicon on insulator (SOI), 76
  silicon transistors, 13
Silicon Image Panellink, 683
SIMMs (single inline memory modules), 376
  30-pin SIMM, 377
  72-pin SIMM, 377
  purchasing, 397
Simon computer, 22
Single Chip AT (SCAT) chipsets, 194
single data rate (SDR) DIMMs, 368, 383
single-density encoding, 487
single edge contact cartridge (SECC), 80
single edge processor package (SEPP), 80
single event upsets (SEUs), 389
single inline memory modules. See SIMMs
single-level cell (SLC), 555-556
single rank memory modules, 376
single-bit error-correction double-bit error detection (SEC-DED), 391
single-gap heads, 481
single-sided memory modules, 376
singleword DMA (direct memory access), 429-430
SiS (Silicon Integrated Systems) chipsets, 231, 242
SIW, 293
SIW (System Information for Windows), 452, 1097
size
  flash memory devices, 549
  hard disk drive platters, 522
  video monitors, 707-708
skins (keyboard), 813
Skull Backlighting setting (BIOS Onboard Devices menu), 317
slave drives (ATA), 426
SLC (single-level cell), 555-556
Sleep-and-Charge (USB), 767-768
sleep feature for speakers, 754
sliders (head), 483-486
slimline cases, 997
SLI (scalable link interface)
  power connectors, 949-953
  PCIe lanes, 706-707
  SLI-ready power supplies, 960
  SLI (scan-line interfacing), 704
slot load mechanism (CD/DVD drives), 647
slots (processor), 189-192
Smart Cat Pro Touchpad, 825
SmartMedia, 551
Smartronix, 1070
S.M.A.R.T. (Self-Monitoring, Analysis, and Reporting Technology), 415, 544-546
S.M.A.R.T. setting (BIOS SATA Drives menu), 322
SMI (System Management Interrupt), 65
SMM (System Management Mode), 65-66
SMR (Shingled Magnetic Recording), 497-498
snooping (bus), 65
SNR (signal-to-noise ratio), 735
S/N (signal-to-noise ratio), 735
socketed op amp chips, 744
sockets, 189-192
LIF (low insertion force), 84
Socket AM1 (Socket FS1B), 92-93
Socket AM2, 89-91
Socket AM2+, 90-91
Socket AM3, 90-91
Socket AM3+, 91
Socket F (1207FX), 91
Socket FM1, 92
Socket FM2, 92
Socket FM2+, 92
Socket LGA775, 84-85
Socket LGA1150, 89
Socket LGA1155, 87
Socket LGA1156, 85-86
Socket LGA1366, 86-87
Socket LGA2011, 87
Socket LGA2011-v3, 89
specifications, 80-83
ZIF (zero insertion force), 78, 84
SODIMMx setting (BIOS main menu), 314
Soft Adjacent Layer (SAL) structure, 482
soft error rates (SERs), 358, 389-390
soft memory fails, 389-390
Soft Power, 906, 912
soft-off switches, 925
software
copyright protection, 24
industry control of, 23-25
optimization, 700
reverse-engineering, 24
software RAID, 474
software resources, 1006-1007
troubleshooting, 1089
SOI (silicon on insulator), 76
solid-state floppy disk card (SSFDC), 551
solid-state drive. See SSD (solid-state drive)
Sony
3.5" half-height drives, 502
CD-ROM design and development, 570-571
DRM (digital rights management), 636
Memory Stick, 552
Memory Stick Micro, 552
Memory Stick PRO-XC, 552
Sound Blaster, 736
Sound Blaster Pro, 736
sound cards
AdLib, 736
choosing, 1005
connectors, 740-744
analog RCA, 743
aux in, 743
cocoal PDIF, 742
HDMI (High Definition Multimedia Interface), 743
line in sound card connectors, 741
line out sound card connectors, 741
microphone in connectors, 742
MIDI in/out, 743
mono in connectors, 742
optical SPDIF out, 742
rear out sound card connectors, 742
socketed op amp chips, 744
world clock I/O, 743
XLR input/output, 743
data compression, 746-747
defined, 31
drivers, 747
frequency response, 734
doctrine of, 736
integrated audio chipsets, 748
Microsoft Windows audio support, 736
3D gaming standards, 738-739
core audio APIs, 737-738
DirectX, 737
EAX (environmental audio extensions), 739
legacy audio support, 740
OpenAL, 738
MIDI support features, 745-746
monophonic/stereophonic, 745
sampling, 735-736
signal processing methods, 743
SNR (signal-to-noise ratio), 735
Sound Blaster, 736
Sound Blaster Pro, 736
sound production features, 748
sound properties, 734
total harmonic distortion, 734
troubleshooting, 749
advanced features, 752
low volume, 750
no sound, 750
problems playing specific file formats, 751
scratchy sound, 751-752
speakers, 751
startup problems, 752
with Device Manager, 752
USB-based audio processors, 745
volume control, 745
Sound Forge, 748
sound. See audio source (MOSFETs), 12
southbridge chipsets, 197-199
spatial streams, 865
S/PDIF sound card connectors, 742
speakers
amplification, 753
collectors, 254
DBB (dynamic bass boost), 754
explained, 753
frequency response, 735
interference, 735
satellite speakers, 754
sleep feature, 754
surround sound, 754-755
total harmonic distortion, 753
troubleshooting, 751
volume control, 754
watts, 753

Specialized Products
Company, 1069

speculative execution, 69-70
speed
BD drives, 644
CD drives
  access times, 645
  buffers/cache, 646
CAV (constant angular velocity), 640
CLV (constant linear velocity), 640-643
data transfer rates, 640
DMA and Ultra-DMA, 646
table of drive speeds/transfer rates, 641
CD-R speed ratings, 587-588
DVD drives, 641-645
  access times, 645
  buffers/cache, 646
DMA and Ultra-DMA, 646
flash memory cards, 561-562
HDDs (hard disk drives)
  average access times, 542
  average seek times, 541
  cache programs, 542
  interleave, 543
  latency, 541-542
  transfer rates, 539-541
memory speed
cache, 65
clock speeds, 363
cycle times, 363
DDR SDRAM, 369-370
DDR2 SDRAM, 371-372
DDR3 SDRAM, 373-374
DDR4 SDRAM, 375
GHz (gigahertz), 362
interleaving, 366
MHz (megahertz), 362
module speeds, 388
nanoseconds, 362
processor bus speeds, 363-365
SDRAM, 368
NICs (network interface cards), 870

overclocking
  bus speeds and multipliers, 149
  CPU voltage settings, 152
  Haswell processors, 152
  Ivy Bridge processors, 151
  modern PC clocks, 145-147
  pitfalls, 149-151
  quartz crystals, 142-145
  Sandy Bridge processors, 151
tips and guidelines, 147-148
  unlocking cores, 148-149
  processors, 55-58
Wi-Fi networks, 867
video RAM, 676

Speed setting (BIOS Performance menu), 330
SpeedFan, 1055
SPGA (staggered pin grid array, 78
spills on keyboards, 813
spin rates (HDDs), 504
spin-coating process (CD-R), 585
spin-valve heads, 482-483
spindle motors, 534-535
Spitfire (Durion), 123
splash screens, 293
SPS (standby power supply), 985-986
SPSYNC (spindle synchronization signal), 426
staggered thin-film media, 523
spattering, 480, 523
SRAM (static RAM). See also cache
  compared to DRAM, 359
  explained, 359
  hits/misses, 360
  Level 1 cache, 360
  Level 2 cache, 360
  Level 3 cache, 361
SSD (solid-state drive)
  applications, 557-558
  configuration
    automatic drive detection, 1030-1031
    explained, 1027-1028
    defined, 553
  Flash-based SSDs, 554-555
  installation, 1028-1030
  MLC (multilevel cell), 555-556
  partition alignment, 557
  SLC (single-level cell), 555-556
  SSD awareness in Windows, 556
  TLC (triple-level-cell), 555-556
  TRIM command, 556-557
  virtual SSD (RAMdisk), 554
SSE (Streaming SIMD Extensions), 68
SSFDC (solid-state floppy disk card), 551
SSIDs, 890
Stabilant 22a, 800, 1078
stepping pin grid array (SPGA), 78
standard parallel ports, 791
standard recording, 516
standard thick client, 997
standard thin client, 997
standby power supply, 985-986
Standby state (APM), 965
Stanley Supply & Services, 1064, 1069
star topology, 883, 888
StarBand, 843
start bits, 785
start-stop communications, 847
startup process, troubleshooting, 752
Startup Sound setting (BIOS Boot menu), 342
Static Column memory, 365-366
static contrast ratio, 715
static electricity, 1083
static-filled sound, troubleshooting, 751-752
static RAM. See SRAM (static RAM)
  status LEDs (broadband devices), 851-852
stepper motors, 526
steppers, 76
stereophonic sound cards. See sound cards
STFT, 718
STOP errors, 1090
stored-program technique, 11
STP (shielded twisted-pair) cables, 872-873
Streaming SIMD Extensions (SSE), 68
Streamroller processors, 137
striping disks, 472-473
STR (Suspend to RAM), 970-971
stuck keyswitches, troubleshooting, 812
stuck pixels (LCDs), 730
subcode bytes (CDs), 578-579
subpixels, 717
substrate material (magnetic storage), 477
Super Audio CD (SA-CD), 623-624
Super Density (SD) disks, 593
Super I/O chips, 197-199, 244
Super Video CDs, 623
Super-IPS (in-place switching), 718
Superchips, 290
SuperFetch, 564
superparamagnetic limit, 524
superscalar technology, 66-67, 100
SuperSpeed USB (USB 3.0), 768-770
SuperSpeed + USB (USB 3.1), 771-772
supertiling, 705
supervisor passwords, 334
Supervisor Password setting (BIOS Security menu), 336
surge protectors, 984
surprise removal, 780
surround sound, 754-755
Suspend setting (BIOS Security menu), 336
Suspend state (APM), 965
Suspend to RAM (STR), 970-971
swabs, 1079
switches, 883-884, 899
   address storing, 884
   compared to hubs, 884-885
dual-speeds, 885
   front panel AC switches, 927-928
   front panel motherboard-controlled, 925-927
   integral AC switches, 927
   managed/unmanaged, 883
   placement of, 886
   ports, 885
   power-saving features, 885
switching power supply
   loads, 953-954
   apparent power, 959
   inductive, 958
   load regulation, 958
   maximum load current, 958
   minimum load current, 958
   reactive power, 959
   resistive, 958
   working power, 959
   overview, 904, 953-954
Symantec Norton Ghost, 546
Symmetrical DSL (SDSL), 838
Sync sector field, 508
synchronous DRAM (SDRAM), 367-368
Synchronous Graphics RAM (SGRAM), 675
synthetic benchmarks, 54
SYmark 2012, 58
System Agent Voltage Override setting (BIOS Performance menu), 331
system assembly
   cables, 1006, 1033
   cases, 997-998, 1018-1021
   cover assembly, 1033
   custom PC configurations, 995-997
   audio/video editing systems, 996
   gaming systems, 996
   graphics systems, 995
   home server systems, 996-997
   home theater systems, 996
   standard thick client, 997
   standard thin client, 997
   virtualization systems, 996
documentation of physical configuration, 1010
ESD (electrostatic discharge) protection, 1009-1010
expansion cards, 1033
explained, 993-998, 1007
hardware resources, 1006-1007
HDDs (hard disk drives)
   choosing, 1003
   drive configuration, 1027-1028
   drive installation, 1028-1030
heatsinks, 1005-1006, 1011-1017
input devices, 1004
memory modules, 1017
miscellaneous hardware, 1006
motherboards, 1026-1027
   BIOS, 1000-1001
   cables, 1026
   chipsets, 999-1000
   Desktop Form Factors website, 999
   explained, 999
   integrated adapters, 1002
   memory, 1001
   mounting in case, 1018-1021
   ports, 1001-1003
   UEFI (Unified Extensible Firmware Interface), 1001
operating system installation, 1035-1036
power supply
   connecting, 1023-1025
   modular power supplies, 1023
   preparation, 1007-1009
   processors, 998-999, 1011-1017
   required tools, 1007-1009
   software resources, 1006-1007
   sound cards, 1005
SSDs (solid-state drives)
   automatic drive detection, 1030-1031
   drive configuration, 1027-1028
   drive installation, 1028-1030
troubleshooting, 1037
video adapters, 1004-1005
   installation, 1031
   removing, 1033
system boards. See motherboards
system boot process. See boot process
System Date setting (BIOS main menu), 315
System Fan Control setting (BIOS Fan Control & Real-Time Monitoring menu), 328
System Fan Speed setting (BIOS Fan Control & Real-Time Monitoring menu), 328
System Information for Windows (SIW), 452, 1097
system interface (video)
  AGP (Accelerated Graphics Port), 678-679
  overview, 678
  PCIe (PCI Express), 679
system logical memory layout, 405-408
System Management Interrupt (SMI), 65
System Management Mode (SMM), 65-66
system memory. See RAM (random access memory)
system passwords, 334
system resources, 270-271
  DMA (direct memory access) channels, 276
  I/O port addresses, 276-277
  IRQs (interrupt request channels)
    8-bit ISA bus interrupts, 272
    16-bit ISA/EISA/MCA bus interrupts, 273-274
    Advanced Programmable Interrupt, 275
    conflicts, 275
    edge-triggered interrupt sensing, 271
    interrupt sharing, 272
    maskable interrupts, 272
    PCI interrupts, 275
    PCI IRQ Steering, 272
System Restore, 1076
system startup, 1033-1035
System Time setting (BIOS main menu), 315
system tray, 779
system types, 29-30

T

T-1 connections, 845
tables, GPT (GUID Partition Table), 470-471
TAC Design Guide, 161
tailgates, 417
Tanisys, 400, 1073
 TA0 (track-at-once) recording, 620
tape drives, 567
TASC (Thermally Advantaged Small Chassis) Design Guide, 161
tCL setting (BIOS Performance menu), 332
TCP/IP, 892-893
TDC Current Limit Override (Amps) setting (BIOS Performance menu), 333
TDP Power Limit Override (Watts) setting (BIOS Performance menu), 333
Teal, Gordon, 6
Technical Committee T13, 412
telephony connectors, 254
temperature acclimation (HDDs), 534
temperature probes, 1074
tessellation (DirectX), 702
test equipment
  DMMs (digital multimeters), 1067, 1070-1071
electrical testing equipment, 1069
electric screwdrivers, 1074
  logic probes, 1071
  loopback connector, 1069-1070
memory testers, 1072-1074
outlet testers, 1072
testing
  burn-in testing, 1054-1055
  cables, 811
  manufacturing tests, 349
  monitors, 726-729
NICs (network interface cards), 899
power supply
  back probing, 976-977
digital infrared thermometers, 979
  DMMs (digital multimeters), 974-977
  power supply testers, 977-978
  variable voltage transformers, 979-980
processors, 77, 94-95
video adapters, 726-727
Tether, 849
tethering, 831, 849
texture mapping, 697-699
tFAW setting (BIOS Performance menu), 331
TF (thin film) heads, 480
TFT (thin film transistor) arrays, 717-718
TFX12V power supply, 918-920
THD (total harmonic distortion), 734, 753
theater surround sound, 754-755
thermal interface material (TIM), 1014
thermal recalibration (servo mechanisms), 529
thermal resistance, 156
thermal shock, 968-969
thermally advantaged chassis cooling fans, 159-160
  maximum heatsink inlet temperatures, 160
  processor ducts, 161
  specifications, 160-161
Thermally Advantaged Small Chassis (TASC) Design Guide, 161
thermometers
digital infrared thermometers, 979
  infrared thermometers, 1074-1075
thick Ethernet coaxial cables, 871-872
Thicknet, 871-872
thin Ethernet coaxial cables, 872
thin-film media, 523
thin film (TF) heads, 480
thin film transistor (TFT) arrays, 717-718
thin form factor (TFX12V) power supply, 918-920
Thinnet, 872
Thomas, Thampy, 121
threads, 72
thumb flash memory devices, 547
Thunderbolt Controller setting (BIOS Onboard Devices menu), 316
Thunderbolt technology, 782-784
<table>
<thead>
<tr>
<th>Term</th>
<th>Page(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM (thermal interface material)</td>
<td>1014</td>
</tr>
<tr>
<td>timeline of computer history</td>
<td>5-10</td>
</tr>
<tr>
<td>TLB (translation lookaside buffer)</td>
<td>65</td>
</tr>
<tr>
<td>TLC (triple-level-cell)</td>
<td>555-556</td>
</tr>
<tr>
<td>TMDS (Transition Minimized Differential Signaling)</td>
<td>683</td>
</tr>
<tr>
<td>Token-Ring</td>
<td>882</td>
</tr>
<tr>
<td>topologies</td>
<td></td>
</tr>
<tr>
<td>bus</td>
<td>881-882</td>
</tr>
<tr>
<td>explained</td>
<td>880-881</td>
</tr>
<tr>
<td>point-to-point</td>
<td>889</td>
</tr>
<tr>
<td>ring</td>
<td>882-883</td>
</tr>
<tr>
<td>star</td>
<td>883, 888</td>
</tr>
<tr>
<td>Topre keyswitch</td>
<td>801</td>
</tr>
<tr>
<td>toroids</td>
<td>1084</td>
</tr>
<tr>
<td>Toshiba xD-Picture Card</td>
<td>553</td>
</tr>
<tr>
<td>total harmonic distortion (THD)</td>
<td>734, 753</td>
</tr>
<tr>
<td>Total Memory setting (BIOS main menu)</td>
<td>315</td>
</tr>
<tr>
<td>touch keyboards</td>
<td>804</td>
</tr>
<tr>
<td>touch pads</td>
<td>824-825</td>
</tr>
<tr>
<td>touch-sensitive mice</td>
<td>820</td>
</tr>
<tr>
<td>touchscreens</td>
<td>719-720</td>
</tr>
<tr>
<td>interfacing</td>
<td>719-720</td>
</tr>
<tr>
<td>setup</td>
<td>720</td>
</tr>
<tr>
<td>technologies</td>
<td>719</td>
</tr>
<tr>
<td>tower cases</td>
<td>998</td>
</tr>
<tr>
<td>TPI (tracks per inch)</td>
<td>505</td>
</tr>
<tr>
<td>track-at-once (TAO) recording</td>
<td>620</td>
</tr>
<tr>
<td>track following systems</td>
<td>527</td>
</tr>
<tr>
<td>track pads</td>
<td>824-825</td>
</tr>
<tr>
<td>trackballs</td>
<td>814, 825</td>
</tr>
<tr>
<td>TrackPoint pointing device</td>
<td>822-824</td>
</tr>
<tr>
<td>tracks. See also sectors</td>
<td></td>
</tr>
<tr>
<td>CDs</td>
<td>575</td>
</tr>
<tr>
<td>defined</td>
<td>507</td>
</tr>
<tr>
<td>densities</td>
<td>505</td>
</tr>
<tr>
<td>DVDs</td>
<td>595</td>
</tr>
<tr>
<td>HDDs</td>
<td>503</td>
</tr>
<tr>
<td>tracks per inch (TPI)</td>
<td>505</td>
</tr>
<tr>
<td>trailers (sectors)</td>
<td>508</td>
</tr>
<tr>
<td>transceivers</td>
<td>829, 837</td>
</tr>
<tr>
<td>transfer modes</td>
<td></td>
</tr>
<tr>
<td>PATA DMA (direct memory access)</td>
<td>429-430</td>
</tr>
<tr>
<td>PATA PIO (Programmed I/O)</td>
<td>429</td>
</tr>
<tr>
<td>SATA (Serial ATA)</td>
<td>445-446</td>
</tr>
<tr>
<td>transfer rates</td>
<td></td>
</tr>
<tr>
<td>CD drives</td>
<td>640</td>
</tr>
<tr>
<td>DMA (direct memory access)</td>
<td>430</td>
</tr>
<tr>
<td>HDDs (hard disk drives)</td>
<td>500, 539-541</td>
</tr>
<tr>
<td>PATA DMA (direct memory access)</td>
<td>429-430</td>
</tr>
<tr>
<td>PATA PIO (Programmed I/O)</td>
<td>429</td>
</tr>
<tr>
<td>SATA (Serial ATA)</td>
<td>432</td>
</tr>
<tr>
<td>transformers, variable voltage, 979-980</td>
<td></td>
</tr>
<tr>
<td>transient response (power supply), 957</td>
<td></td>
</tr>
<tr>
<td>transistors</td>
<td></td>
</tr>
<tr>
<td>Graphene-based, 13</td>
<td></td>
</tr>
<tr>
<td>invention of, 11-12</td>
<td></td>
</tr>
<tr>
<td>MOSFETs (Metal Oxide Semiconductor Field Effect Transistors), 12-13</td>
<td></td>
</tr>
<tr>
<td>PMOS, 13</td>
<td></td>
</tr>
<tr>
<td>silicon, 13</td>
<td></td>
</tr>
<tr>
<td>Tri-Gate, 13-14</td>
<td></td>
</tr>
<tr>
<td>transition cells, 478</td>
<td></td>
</tr>
<tr>
<td>Transition Minimized Differential Signaling (TMDS), 683</td>
<td></td>
</tr>
<tr>
<td>translation</td>
<td></td>
</tr>
<tr>
<td>CHS bit-shift translation, 457-459</td>
<td></td>
</tr>
<tr>
<td>LBA-assist translation, 462-464</td>
<td></td>
</tr>
<tr>
<td>translation lookaside buffer (TLB), 65</td>
<td></td>
</tr>
<tr>
<td>Transmission Control Protocol/Internet Protocol (TCP/IP), 892-893</td>
<td></td>
</tr>
<tr>
<td>tRASmin setting (BIOS Performance menu), 331</td>
<td></td>
</tr>
<tr>
<td>tRASmin setting (BIOS Performance menu)</td>
<td></td>
</tr>
<tr>
<td>tREF, 358</td>
<td>332</td>
</tr>
<tr>
<td>tri-channel memory, 388</td>
<td></td>
</tr>
<tr>
<td>Tri-Gate transistors, 13-14</td>
<td></td>
</tr>
<tr>
<td>TRIM command, 556-557</td>
<td></td>
</tr>
<tr>
<td>triodes, 11</td>
<td></td>
</tr>
<tr>
<td>triple-level-cell (TLC), 555-556</td>
<td></td>
</tr>
<tr>
<td>Tripp Lite, 988</td>
<td></td>
</tr>
<tr>
<td>troubleshooting. See also diagnostic software; errors; testing</td>
<td></td>
</tr>
<tr>
<td>3TB drives, 1098</td>
<td></td>
</tr>
<tr>
<td>adapter cards, 1089-1090, 1100</td>
<td></td>
</tr>
<tr>
<td>audio, 1092</td>
<td></td>
</tr>
<tr>
<td>advanced features, 752</td>
<td></td>
</tr>
<tr>
<td>Device Manager, 752</td>
<td></td>
</tr>
<tr>
<td>low volume, 750</td>
<td></td>
</tr>
<tr>
<td>no sound, 750</td>
<td></td>
</tr>
<tr>
<td>problems playing specific file formats, 751</td>
<td></td>
</tr>
<tr>
<td>scratchy sound, 751-752</td>
<td></td>
</tr>
<tr>
<td>sound cards, 749</td>
<td></td>
</tr>
<tr>
<td>speakers, 751</td>
<td></td>
</tr>
<tr>
<td>startup problems, 752</td>
<td></td>
</tr>
<tr>
<td>basic guidelines, 1085</td>
<td></td>
</tr>
<tr>
<td>BD (Blu-ray), 653</td>
<td></td>
</tr>
<tr>
<td>BIOS error messages, 348-349</td>
<td></td>
</tr>
<tr>
<td>AMI BIOS, 351</td>
<td></td>
</tr>
<tr>
<td>Award BIOS, 351</td>
<td></td>
</tr>
<tr>
<td>Compaq BIOS, 351</td>
<td></td>
</tr>
<tr>
<td>IBM BIOS, 350-351</td>
<td></td>
</tr>
<tr>
<td>Insyde BIOS, 352</td>
<td></td>
</tr>
<tr>
<td>Phoenix BIOS, 352</td>
<td></td>
</tr>
<tr>
<td>boot process, 1089, 1096</td>
<td></td>
</tr>
<tr>
<td>bootable CDs, 652</td>
<td></td>
</tr>
<tr>
<td>bootstrap approach, 1087-1088</td>
<td></td>
</tr>
<tr>
<td>broadband service</td>
<td></td>
</tr>
<tr>
<td>interruptions, 849</td>
<td></td>
</tr>
<tr>
<td>broadband signal lights, 851-852</td>
<td></td>
</tr>
<tr>
<td>BSOD (Blue Screen Of Death) errors, 1053</td>
<td></td>
</tr>
<tr>
<td>CD/DVD drives, 1098</td>
<td></td>
</tr>
<tr>
<td>disc burning, 652</td>
<td></td>
</tr>
<tr>
<td>disc read failures, 649-652</td>
<td></td>
</tr>
<tr>
<td>disc write failures, 650-651</td>
<td></td>
</tr>
<tr>
<td>firmware, 654-655</td>
<td></td>
</tr>
<tr>
<td>slow drive speeds, 651</td>
<td></td>
</tr>
<tr>
<td>CMOS batteries, 991-992</td>
<td></td>
</tr>
<tr>
<td>DVDs, 599-600</td>
<td></td>
</tr>
<tr>
<td>emergency flash BIOS recovery, 300-302</td>
<td></td>
</tr>
<tr>
<td>ESD (electrostatic discharge), 1009-1010</td>
<td></td>
</tr>
<tr>
<td>Fatal Exception errors, 1091</td>
<td></td>
</tr>
<tr>
<td>frozen/locked systems, 1095-1099</td>
<td></td>
</tr>
<tr>
<td>HDDs (hard disk drives), 1095-1099</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** The document contains a wide range of computer hardware and software terms, focusing on troubleshooting, error messages, and system components. It highlights various aspects such as BIOS settings, memory settings, diagnostics, and hardware specifications. The text is structured to provide comprehensive information for users and professionals alike.
twisted-pair cables

Index

1157

Internet connections, 1091
IRQs (interrupt request channels) conflicts, 275
keyboards, 811, 1091-1092
cleaning, 812-813
connectors, 812
defective cables, 811-812
stuck keyswitches, 812
known-good spare technique, 1087
maintenance tools, 1063-1064, 1068
2.5" ATA drive cables and adapters, 1067
3.5" drive enclosure, 1068
cleaning materials, 1067
data transfer cables and adapters, 1067
DMMs (digital multimeters), 1067, 1070-1071
electric screwdrivers, 1067, 1074
electrical testing equipment, 1069
ESD (electrostatic discharge) protection kits, 1068
files, 1067
flashlights, 1067
hemostats, 1067
infrared thermometers, 1074-1075
lithium coin cell batteries, 1068
logic probes, 1071
loopback connector, 1069-1070
marketers/pens, 1067
memory testers, 1072-1074
needle-nose pliers, 1067
nut drivers, 1065
nylon cable-ties, 1067
outlet testers, 1072
parts grabbers, 1065, 1075
POST cards, 1067
safety, 1068-1069
spare keyboard/mouse, 1068
spare parts, 1068
temperature probes, 1074
Torx drivers, 1065
tweezers, 1065
vises/clamps, 1067
Windows install media, 1067
wire cutters, 1067
wire strippers, 1067
MBR errors, 348-349, 352-353
memory
ECC (error correcting code), 391-392
hard fails, 389
parity checking, 390-391
soft errors, 389-390
mice, 821
microphones, 756
Missing operating system error message, 1096
monitors, 728-731, 1092-1093
bad pixels, 730
dead pixels, 730
monitor adjustments, 729
monitor repairs, 731-732
monitor testing, 728-729
stuck pixels, 730
motherboard installation, 1099
PCIe x16 video cards, 1100
POST (power on self test). See POST power supply, 972-973, 1090
diagnostic procedures, 973
bad pixels, 730
dead pixels, 730
monitor adjustments, 729
monitor repairs, 731-732
monitor testing, 728-729
stuck pixels, 730
Trusted Platform Module setting (BIOS Onboard Devices menu), 317
tubes, vacuum, 11-12
Turing, Alan, 5
Turing Machine, 5
turning off/on systems
electrical costs, 969-970
S3 (Suspend To RAM) state, 970-971
S4 (Hibernate) state, 971
thermal shock, 968-969
TV display interfaces, 695-696
tweezers, 1065
twisted-pair cables
building, 875-879
cable distance limitations, 878-880
Category 3 cable, 874
Category 5 cable, 874
Category 6 cable, 874
Category 6a cable, 874
crossover cables, 877
grounding loops, 873
STP (shielded twisted-pair), 872-873
wiring standards, 875-876
tWR setting (BIOS Performance menu), 332

tWTR setting (BIOS Performance menu), 332

Type-C cable, 772
typematic functions, 805-806

U

UART (Universal Asynchronous Receiver/Transmitter) chip, 788
UDF Reader 2.5, 632
UDF (Universal Disk Format), 620, 632-633
UDF Volume Reader 7.1.0.95, 632
UDMA (Ultra-DMA), 416-418
Udpixel, 730
UEFI Boot setting (BIOS Boot menu), 342
UEFI Microsoft PnP ACPI Registry, 347
UEFI (Unified Extensible Firmware Interface). See UEFI
unified memory architecture (UMA), 659
UniGine Heaven DX11, 704
Uninterruptible power supply. See UPS
Upgrading and Repairing Servers (Mueller), 757

Uncore Multiplier setting (BIOS Performance menu), 331
Uncore Voltage Override setting (BIOS Performance menu), 331
“Understanding SD Association Speed Ratings” (Lexar), 562
Under-Speed Threshold setting (BIOS Fan Control & Real-Time Monitoring menu), 328
Under-Voltage Threshold setting (BIOS Fan Control & Real-Time Monitoring menu), 328
Underwriters Laboratories. See UL
Unicomp, 803, 813
Unified Extensible Firmware Interface. See UEFI (Unified Extensible Firmware Interface)
unified memory architecture (UMA), 659
Uninterruptible power supply. See UPS
UNIVAC (Universal Automatic Computer), 11
USB 3.0 Controller setting (BIOS USB menu), 318
USB 3.0 Hub setting (BIOS USB menu), 318

u-pipes, 101
uplink ports, 886
UPS (uninterruptible power supply), 986-988
USB (Universal Serial Bus)
CD/DVD drives, 647
connectors
Mini/Micro A/B connectors, 766
mini plugs and sockets, 766
Series A/B connectors, 766
USB 1.1-2.0 header connector pinout, 249
USB 3.0 header connector pinout, 251
explained, 758-759
functions, 760
hot-plugging, 779-782
hubs, 758-760
keyboards, 810
legacy support, 805
maximum cable lengths, 762
mice interfaces, 818
Power Delivery, 773
power usage, 761
security risks, 774-775
troubleshooting, 1098
Type-C cable, 772
USB 1.1
connectors, 764-767
technical details, 759-763
USB 1.1-2.0, 761
USB 2.0
connectors, 764-767
data rates, 763-764
technical details, 759-763
USB 3.0, 558, 768-770
USB 3.1, 771-772
USB-based audio processors, 745
USB/FireWire cable adapter, 1068
USB flash drives, 558-559
USB On-The-Go, 773-774
USB Sleep-and-Charge, 767-768
Windows USB support, 774
WUSB (Wireless USB), 774
USB 3.0 Controller setting (BIOS USB menu), 318
USB 3.0 Hub setting (BIOS USB menu), 318

untended BIOS Configuration setting (BIOS Security menu), 336
USB Boot setting (BIOS Boot menu), 342
USB-IF (USB Implementer’s Forum), 764
USB Implementer’s Forum (USB-IF), 764
USB Legacy setting (BIOS USB menu), 318
USB menu (BIOS Setup), 317-319
USB Optimization setting (BIOS Boot menu), 343
USB Port x setting (BIOS USB menu), 318
User access Level setting (BIOS Security menu), 336
User passwords, 334
User Password setting (BIOS Security menu), 336
user-created bootable media, upgrading flash ROM from, 299-300
user-supported diagnostic software, 1055
UTP (unshielded twisted-pair) cables, 872
building, 875-879
cable distance limitations, 878-880
Category 3 cable, 874
Category 5 cable, 874
Category 6a cable, 874
Category 6 cable, 874
crossover cables, 877
wiring standards, 875-876
U-verse, 894
UWB (ultrawideband), 774

V

V-Link, 201
vacuum cleaners, 812, 1079
vacuum tubes, 11-12
VAIO, 552
variable voltage transformers, 979-980
VBR (volume boot record), 1096
VCD (Video CD), 622-623
VDSL (Very High-Data-Rate DSL), 838
vendor-unique commands (ATA), 447
vertical blanking interval, 714
vertical frequency, 714
vertical recording, 495
vertices, 699
Very High-Data-Rate DSL (VDSL), 838
VESA (Video Electronic Standards Association), 264, 682
VGA (Video Graphics Array), 680-682, 722
VIA Technologies
chipsets, 201, 232, 242
ITX motherboards, 187-189
Mini-ITX motherboards, 187-189
VIA VT, 74
video adapters. See also 3D graphics accelerators
BIOS Setup, 323-327
chipsets, 659-663, 673
choosing, 1004-1005
components, 671-672
DAC (digital-to-analog converter), 678
defined, 658
heterogeneous adapters, 723
homogeneous adapters, 723
installation, 1031
optimizing system for, 996
overview, 658
processors with integrated video, 663-666
AMD, 667-670
Intel, 665-667
removing, 1033
testing, 726-727
troubleshooting, 725-726
types of, 658-659
UMA (unified memory architecture), 659
video BIOS, 672
video drivers, 727
VRAM, 675

video BIOS, 672
video cards
defined, 31
onboard BIOS, 292
PCI x16 video cards, 1100
troubleshooting, 1093
Video CD (VCD), 622-623
video display interface
digital display interfaces, 682-683
DisplayPort, 690-694
DMS-59, 686
DVI (Digital Video Interface), 683-686
HDMI (High Definition Multimedia Interface), 686-690
overview, 679-680
TV display interfaces, 695-696
VGA (Video Graphics Array), 680-682
video drivers, 727
Video Electronic Standards Association (VESA), 264, 682
Video Graphics Array (VGA), 680-682
Video menu (BIOS Setup), 323-326
video monitors. See monitors
Video Optimization setting (BIOS Boot menu), 343
video RAM (random access memory), 674-675, 707
DDR SDRAM, 675
GDDR2 SDRAM, 675
GDDR3 SDRAM, 675
GDDR4 SDRAM, 676
GDDR5 SDRAM, 676
RAM calculations, 676-677
SGRAM, 675
speed, 676
video memory bus width, 677-678
VRAM, 675
WRAM, 675
video system interface
AGP (Accelerated Graphics Port), 678-679
overview, 678
PCIe (PCI Express), 679
vintagecalculators.com, 22
virgin CDs, 585
virtual PC environments, 740
virtual real mode, 98
virtual SSD (RAMdisk), 554
virtualization
   hardware-assisted
   virtualization support
      AMD-V, 73
      enabling, 74
      Intel VT-D, 74
      Intel VT-x, 74
      VIA VT, 74
   legacy audio support, 740
   optimizing system for, 996
viruses, CIH, 295
vices, 1067
visible surface determination, 700
Vista/Win7 Codec Packages, 628
VL-Bus, 264
voice-coil actuators, 526-528
volatile storage, 356
voltage regulator module (VRM), 939-940
voltage settings (processors), 93-94, 152
volume. See also audio
   sound cards, 745
   speaker volume control, 754
   troubleshooting, 750
volume boot record (VBR), 1096
v-pipes, 101
VRAM (Video RAM), 675
VRM (voltage regulator module), 939-940

W

wafers, 75-77
wait states, 55, 360
Wake on LAN connectors, 254
Wake on LAN from S4/S5 setting (BIOS Power menu), 340
Wake on Ring connectors, 254
Wake system from S5 setting (BIOS Power menu), 340
Wakeup Date setting (BIOS Power menu), 340
Wakeup Hour setting (BIOS Power menu), 340
Wakeup Minute setting (BIOS Power menu), 340
Wakeup Second setting (BIOS Power menu), 340
WANs (wide area networks), 854
war driving, 889
WASAPI (Windows Audio Session API (WASAPI) API, 737
Watchdog Coverage for Host Clock setting (BIOS Performance menu), 330
waterblocks, 1006
watts, 753
Waveform audio, sampling, 735-736
writable adapters, 746
WD1003 commands, 446
wear leveling, 529
WECA (Wireless Ethernet Compatibility Alliance), 862
wedge servo mechanisms, 530
WEP (wired equivalent privacy), 890-891
Western Digital, 500
   ATA. See ATA (AT Attachment)
   WD1003/WD1006 (IBM AT)
   512-byte sector format, 509
White Book standard (Video CD), 622-623
white power switch connector wires, 927
white-box systems, 28-29
wide area networks. See WANs
width
   data buses, 29-30
   processor specifications, 40-41
Wi-Fi (Wireless Fidelity)
   802.11a, 864-865
   802.11ac, 867
   802.11ad, 868
   802.11b, 863-864
   802.11g, 865
   802.11n, 865-867
   access points, 887, 899
   DHCP support, 891
   explained, 862-863
   network speeds, 867
   NICs (network interface cards), 887-888
   point-to-point topology, 889
   security, 889-891
   signal boosters, 888
   specialized antennas, 888
   star topology, 888
   users per access point, 892
   wireless bridges, 888
   wireless repeaters, 888
Wi-Fi Alliance, 862
Wi-Fi Protected Access (WPA), 890
WiGig, 868
WildBlue, 843
Wilkes, Maurice, 6
WiMAX, 840
Winchester drives, 498
Window RAM (WRAM), 675
Windows 3.x drive limitations, 468
Windows 7
   103-key keyboards, 796-798
   audio
      3D gaming audio standards, 738-739
      core audio APIs, 737-738
      EAX (environmental audio extensions), 739
      legacy audio support, 740
      OpenAL, 738
   boot process, 1062-1063
   drive limitations, 469
   networking with, 901
   SSD (solid-state drive)
      awareness, 556
      USB support, 774
Windows 8
   103-key keyboards, 796-798
   audio
      3D gaming audio standards, 738-739
      core audio APIs, 737-738
      EAX (environmental audio extensions), 739
      OpenAL, 738
   boot process, 1063
   Codec Package, 628
   drive limitations, 469
   Fast Startup mode, 1063
   Hyper-V Client, 73
   installation, 1036
   networking with, 901
   SSD (solid-state drive)
      awareness, 556
      USB support, 774
Windows 9x
   103-key keyboards, 796-798
   boot process, 1061
   drive limitations, 468
Windows 10
- boot process, 1063
- core audio APIs, 738
- Hyper-V Client, 73
- USB support, 774

Windows 98, USB support, 774

Windows 2000
- 103-key keyboards, 796-798
- boot process, 1061-1062
- drive limitations, 469

Windows Audio Session API (WASAPI) API, 737

Windows Disk Cleanup tool, 1077

Windows executable upgrades (flash ROM), 296

Windows Me
- 103-key keyboards, 796-798
- boot process, 1061
- drive limitations, 468

Windows Memory Diagnostic, 400, 1074

Windows NT drive limitations, 468

Windows Sound Recorder, 736

Windows Vista
- audio
  - 3D gaming audio standards, 738-739
  - core audio APIs, 737-738
  - EAX (environmental audio extensions), 739
  - legacy audio support, 740
  - OpenAL, 738
- boot process, 1062-1063
- networking with, 901
- USB support, 774

Windows XP
- 103-key keyboards, 796-798
- boot process, 1061-1062
- USB support, 774
- Video Decoder Checkup Utility, 628
- winload.exe, 1062-1063
- wire cutters, 1067
- wire strippers, 1067
- wired equivalent privacy (WEP), 890-891
- Wireless-A, 864-865
- Wireless-AC, 867-868
- wireless bridges, 888
- wireless broadband, 840

Wireless Ethernet Compatibility Alliance (WECA), 862

Wireless Fidelity. See Wi-Fi (Wireless Fidelity)

Wireless-G, 865

wireless input devices, 827
  - Bluetooth, 828
  - IR (infrared), 828
  - multiple devices with single transeiver, 829
  - power management, 828-829
  - proprietary radio frequency, 828
  - troubleshooting, 829

Wireless Internet Service Providers Association (WISPA), 840

Wireless Internet Service Provider (WISP), 840

Wireless-N, 865-867

WirelessNetView (Nirsoft), 1084

wireless networks
  - Bluetooth, 868-869, 889
  - security, 890
  - topologies, 888-889
  - Wi-Fi (Wireless Fidelity)
    - 802.11a, 864-865
    - 802.11ac, 867
    - 802.11ad, 868
    - 802.11b, 863-864
    - 802.11g, 865
    - 802.11n, 865-867
  - access points, 887
  - antennas, 888
  - bridges, 888
  - DHCP support, 891
  - explained, 862-863
  - network speeds, 867
  - NICs (network interface cards), 887-888
  - repeaters, 888
  - security, 889-891
  - signal boosters, 888
  - users per access point, 892

wireless PANs (WPANs), 854

wireless repeaters, 888

Wireless USB (WUSB), 774

wireless WANs (WWANs), 854

WISP (Wireless Internet Service Provider), 840

WISPA (Wireless Internet Service Providers Association), 840

wmic partition get command, 515

wobbled land and groove recording, 607

working power, 959

world clock I/O sound card connectors, 743

WORM (write once, read many), 584

Wozniak, Steve, 7, 36

WPA (Wi-Fi Protected Access), 890

WRAM (Window RAM), 675

wrap plugs, 1069-1070

writable CDs. See CD-R; CD-RW

write once, read many (WORM), 584

write process, 478-479

write protection for flash ROM, 295

write-back cache, 401, 779

write-through cache, 64

write-through operations, 780

WTX motherboards, 173

WUSB (Wireless USB), 774

WWANs (wireless wide area networks), 854

X

XD Technology setting (BIOS Security menu), 337

xD-Picture Card, 553

xDSL. See DSL (digital subscriber line)

Xebec 1210/1220 (IBM XT) 512-byte sector format, 509

XLR input/output sound card connectors, 743

XOP, 69

XQD, 550-551

XT motherboards, 166-167
Y-Z

Yellow Book (CD-ROM) standard, 618
yields, 77

Z80 processor (Zilog), 35
ZBR (zoned-bit recording), 516-518
Z-CLV (zoned CLV) technology, 641
zero insertion force (ZIF) sockets, 78, 84
Ziegler, J. F., 389
ZIF (zero insertion force) sockets, 78, 84
Zilog Z80 processor, 35
zoned-bit recording (ZBR), 516-518
zoned CLV (Z-CLV) technology, 641
zones, 517
Zuse, Konrad, 5