© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Contents

Preface xi

Introduction 1

Part I: Hardware 7

1. What Is a Computer? 11
- 1.1 Logical Construction 13
  - 1.1.1 Processor 14
  - 1.1.2 Primary memory 15
  - 1.1.3 Secondary storage 16
  - 1.1.4 Et cetera 18
- 1.2 Physical Construction 18
- 1.3 Moore's Law 22
- 1.4 Summary 24

2. Bits, Bytes, and Representation of Information 27
- 2.1 Analog versus Digital 27
- 2.2 Analog-Digital Conversion 29
  - 2.2.1 Digitizing images 29
  - 2.2.2 Digitizing sound 30
  - 2.2.3 Digitizing movies 33
  - 2.2.4 Digitizing text 33
- 2.3 Bits, Bytes, and Binary 34
  - 2.3.1 Bits 35
  - 2.3.2 Powers of two and powers of ten 36
  - 2.3.3 Binary numbers 37
  - 2.3.4 Bytes 39
- 2.4 Summary 41

3. Inside the Processor 43
- 3.1 The Toy Computer 44
  - 3.1.1 The first Toy program 44
  - 3.1.2 The second Toy program 46

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

3.1.3 Branch instructions 47
3.1.4 Representation in memory 49
3.2 Real Processors 50
3.3 Caching 53
3.4 Other Kinds of Computers 54
3.5 Summary 56

Wrap-up on Hardware 57

Part II: Software 59

4. Algorithms 63
4.1 Linear Algorithms 64
4.2 Binary Search 66
4.3 Sorting 67
4.4 Hard Problems and Complexity 71
4.5 Summary 74

5. Programming and Programming Languages 75
5.1 Assembly Language 76
5.2 High-Level Languages 77
5.3 Software Development 84
5.3.1 Libraries, interfaces, and development kits 85
5.3.2 Bugs 86
5.4 Intellectual Property 89
5.4.1 Trade secrets 89
5.4.2 Trademarks 89
5.4.3 Copyrights 89
5.4.4 Patents 91
5.4.5 Licenses 92
5.5 Standards 94
5.6 Open Source Software 95
5.7 Summary 97

6. Software Systems 99
6.1 Operating Systems 100
6.2 How an Operating System Works 105
6.2.1 System calls 106
6.2.2 Device drivers 107
6.3 Other Operating Systems 107
6.4 File Systems 108
6.4.1 Secondary storage file systems 110
6.4.2 Removing files 112
6.4.3 Other file systems 113
6.5 Applications 115
6.6 Layers of Software 117
6.7 Summary 118

7. Learning to Program 121
7.1 Programming Language Concepts 122
7.2 A First JavaScript Program 123
7.3 A Second JavaScript Program 124
7.4 Loops and Conditionals 126

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

7.5 JavaScript Libraries and Interfaces 128
7.6 How JavaScript Works 129
7.7 A First Python Program 130
7.8 A Second Python Program 131
7.9 Python Libraries and Interfaces 133
7.10 How Python Works 135
7.11 Programming with AI 136
7.12 Summary 137

Wrap-up on Software 139

Part III: Communications 141

8. Networks 147
8.1 Home Networking 148
8.2 Local Area Networks and Ethernet 149
8.3 Wireless 151
8.4 Cell Phones 153
8.5 Bandwidth 157
8.6 Compression 158
8.7 Error Detection and Correction 160
8.8 Summary 162

9. The Internet 163
9.1 An Internet Overview 164
9.2 Domain Names and Addresses 167
9.2.1 Domain Name System 167
9.2.2 IP addresses 168
9.2.3 Root servers 169
9.2.4 Registering your own domain 170
9.3 Routing 171
9.4 TCP/IP Protocols 174
9.4.1 IP, the Internet Protocol 174
9.4.2 TCP, the Transmission Control Protocol 175
9.5 Higher-Level Protocols 177
9.5.1 Telnet and SSH: remote login 177
9.5.2 SMTP: Simple Mail Transfer Protocol 178
9.5.3 File sharing and peer-to-peer protocols 180
9.6 Copyright on the Internet 181
9.7 The Internet of Things 183
9.8 Summary 184

10. The World Wide Web 187
10.1 How the Web Works 188
10.2 HTML 189
10.3 Cookies 192
10.4 Active Content in Web Pages 193
10.5 Active Content Elsewhere 194
10.6 Viruses, Worms and Trojan Horses 195
10.7 Web Security 197
10.7.1 Attacks on clients 197
10.7.2 Attacks on servers 202

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

10.7.3 Attacks on information in transit 203
10.8 Defending Yourself 204
10.9 Summary 207

Part IV: Data 209

11. Data and Information 211
11.1 Search 212
11.2 Tracking 215
11.3 Social Media 222
11.4 Data Mining and Aggregation 225
11.5 Cloud Computing 227
11.6 Summary 231

12. Artificial Intelligence and Machine Learning 233
12.1 Historical Background 234
12.2 Classical Machine Learning 236
12.3 Neural Networks and Deep Learning 237
12.4 Natural Language Processing 240
12.5 Large Language Models 241
12.5.1 Training 242
12.5.2 Transformers and Attention 243
12.5.3 Generating output 243
12.5.4 Limitations 244
12.5.5 The Future of LLMs 244
12.6 Summary 245

13. Privacy and Security 249
13.1 Cryptography Background 250
13.2 Secret-key Cryptography 252
13.3 Public-key Cryptography 253
13.4 Public-key Crypto in Use 254
13.5 Anonymity 258
13.5.1 Tor and the Tor Browser 259
13.5.2 Bitcoin 261
13.6 Summary 263

14. What Comes Next? 267

Notes 273

Glossary 281

Index 289

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Introduction

> "I fear none of the existing machines; what I fear is the extraordinary rapidity with which they are becoming something very different to what they are at present."
>
> Samuel Butler, *Erewhon*, Chapter XXIII, 1872.

The computing world changed suddenly on November 30, 2022. On that day, OpenAI, a company that few other than technology enthusiasts had even heard of, released a program called ChatGPT that within a couple of months had 100 million users, and today has a billion.

ChatGPT could carry on a sensible conversation in perfect English and other languages as well. It could answer questions, summarize documents, synthesize prose and poetry, all with remarkable fluency and naturalness.

As is often the case in the education business, I learned about ChatGPT from an undergraduate friend, who had been in my class a couple of years earlier. His first thought was to try ChatGPT on my midterm exam. For the record, it did a creditable job, better than at least some members of the class. ChatGPT wasn't great at arithmetic, but then again, that has been true of a discouraging number of students over the years. It sometimes hallucinated, or invented things that showed that its knowledge was imperfect. Of course that was true of students as well. Its prose was sometimes a bit pedestrian or predictable, as when I asked it to write letters to admissions officers about why it wanted to attend Princeton and (separately) Harvard, but there were no grammar or spelling errors. Again, this was better than at least some students I have known.

Even then it was an amazing experience to play with it. Now, after several years of evolution, chatbots like ChatGPT, Claude, Gemini, and a dozen others have become staples of daily life for many people. They are more capable in more areas. Many of the early deficiencies are much reduced—fewer hallucinations, better arithmetic, more sophisticated and polished prose. They still get things wrong or make them up, but less frequently.

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

They can handle much longer inputs. They also do a fine job with different kinds of input, like scanning PDF documents, finding the tables of data within, and converting those to spreadsheet format. They draw pictures and make diagrams. They can carry out extended chains of reasoning, and explain how they are doing it. They now include citations to sources from which they are drawing information. They can even perform actions under some circumstances, like controlling a browser. ‘‘Ironic’’ doesn’t begin to capture what’s going on when a chatbot presses the ‘‘I’m a human’’ checkbox on a web page.

We are in the early stages of what promises to be a revolution in how we work with computers. Some fields have already seen significant effects, and others are sure to. Among the potentially threatened jobs might be legal research (though courts and lawyers have become exquisitely sensitive to the problem of hallucinated legal citations). People who make low-quality infographics or article summaries are likely to become unemployed. Those who translate between major natural languages may be at risk, though not yet for niche ones nor for high-quality literary material. Conspiracy theorists and the creators of fake news, fake images, fake videos and other kinds of misinformation can be replaced by programs that will do it as well but in much greater quantity.

On the search engine front, many people now search with a chatbot rather than with Google or Bing. It’s easier to ask a complicated question or a sequence of them, and the results are likely to be better. Unfortunately, advertisements, clickbait and other junk have arrived or are on the horizon for AI search, and the distinction between AI and conventional search is blurring.

In my own area, computer programming, it’s clear that certain kinds of programming can be done just fine by AI systems. This includes the assignments in introductory programming courses, so naturally students are going to submit solutions that they didn’t write themselves. At the moment, teachers can usually detect that kind of cheating, sometimes because the AI systems are more sophisticated and knowledgeable than typical students would be. Some kinds of entry-level programming can be done sufficiently well by an AI assistant that there is less need for entry-level programmers. That’s likely to be of concern to students looking for jobs and to their instructors, who worry about how to future-proof what we teach them.

Professional programmers use chatbots to assist with their own work; the programs can generate boilerplate code, look up documentation, generate tests, and perform similar tasks quite well. Discussion forums like Hacker News that are frequented by programmers are of several minds on how effective AI assistance is, but on balance more people find it helpful than don’t, and my bet is that AI assistance for programmers will become standard operating procedure.

In short, we’re in the early stages of a massive change in our relationships with computing. Technology has already become deeply embedded in our lives, and although it has improved them in many ways, there’s another side to the story, not so optimistic.

The Internet was already a hotbed of paranoia, hatred and crackpot theories before and during Covid. Today social media has enabled politicians and government officials to spread lies, divide us further, and avoid blame, abetted by ‘‘news’’ outlets with no regard for facts. Sites like Twitter (now called X) and Facebook (now Meta)

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

tried unsuccessfully to find middle ground between being neutral platforms for the free expression of ideas and limiting the barrage of incendiary postings and outright falsehoods. For the most part, they have given up the attempt; money is winning out over a moral position. The technology billionaires who control such sites are not helping.

Surveillance has reached new heights, used in many countries to restrict people and monitor and control their behavior. For instance, China uses face recognition for, among other things, keeping track of its minority populations. During the Covid-19 pandemic, the Chinese government mandated installation of an app that worked as a sort of immunity passport but also reported its users' locations to the police. In the US and the UK, local law enforcement agencies use face recognition, license plate readers, and the like to keep an eye on people. In the US, the Immigration and Customs Enforcement (ICE) agency is using data from many sources in pogrom-like sweeps that round up potentially illegal immigrants.

Our mobile phones continuously monitor our locations and numerous companies can aggregate the data. Tracking applications for smartphones are an excellent example of the double-sided nature of technology. Who could have been against a Covid-19 contact-tracing system that tells you whether you have been exposed to a potentially contagious person? But any technology that enables the government to know where you've been and who you've been talking to also helps it to monitor and control more effectively. It's a short and slippery slope from disease tracking to ferreting out peaceful protesters, dissidents, political enemies, whistle-blowers, and anyone else that the authorities think might be a threat to their power.

For almost all of our interactions with the online world and in the real world as well, countless computer systems watch and remember who we dealt with, how much we paid, and where we were at the time. A large part of this data gathering is for commercial purposes, since the more that businesses know about us, the more accurately they can target us for advertising. Most readers know that such data is collected, but I expect that many would be surprised by how much there is and how detailed. In 2014, Shoshana Zuboff coined the term *surveillance capitalism* to describe how businesses collect and use personal information on a grand scale. It's disturbingly accurate.

Companies are not the only observers; governments are deeply involved in surveillance as well. The NSA emails, internal reports, and PowerPoint presentations disclosed by Edward Snowden revealed much about spying in the digital era. The gist is that the NSA watches everyone on a grand scale.

Snowden's revelations were stunning. It had been widely suspected that the NSA spied on more people than it admitted, but the extent surpassed everyone's imagination. The NSA routinely collected metadata about all telephone calls made in the US—who called who, when they talked, and for how long—and may have recorded the content of these calls as well. It recorded my Skype conversations and email contacts, and probably the mail contents as well. (Yours too, of course.) It tapped the cell phones of world leaders. It intercepted huge amounts of Internet traffic by placing recording devices on equipment where submarine cables enter and leave the US. It enlisted or coerced the major telecommunications and Internet companies to gather and hand over information about their users. It stored great amounts of data for

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

extended periods of time, sharing some of it with spy agencies in other countries.

Meanwhile, back on the commercial front, hardly a day goes by when we don't learn of another breach of security at some company or institution, in which shadowy hacker groups steal names, addresses, credit card numbers, and other personal information about millions of people. Usually these are high-tech criminals, but sometimes it's espionage by other countries, looking for valuable information. From time to time, foolish or careless behavior by whoever maintains the information accidentally exposes private data. No matter what the mechanism, data that has been collected about us is all too often exposed or stolen, potentially to be used against us.

The purpose of this book is to explain the technology—hardware, software, communications—that lies behind all of this, so you understand how such systems operate. How can pictures, music, movies, and intimate details of your personal life be sent around the world in no time at all? How do email and texting work, and how private are they? Why is spam so easy to send and so hard to get rid of? Do cell phones report where you are all the time? Who is tracking you online and on your phone, and why does that matter? Can your face be recognized in a crowd? Who knows that it's *your* face? Can hackers take over your car? How about self-driving cars? Can we defend our privacy and security, or should we just give up? By the end of the book, you should have a decent idea of how computer and communications systems work, how they affect you, and how you can strike a balance between using helpful services and protecting your privacy.

There are only a handful of fundamental ideas, which we will discuss in much more detail in the rest of the book.

First is the *universal digital representation of information*. Complex and sophisticated mechanical systems like those that stored documents, pictures, music and movies for much of the 20th century have been replaced by a single uniform storage mechanism. Information is represented digitally—as numeric values—rather than in specialized forms like colored dyes embedded in plastic film or magnetic patterns on vinyl tape. Paper mail gives way to digital mail. Paper maps yield to digital ones. Paper documents are replaced by online databases. All those disparate analog representations have been replaced by a common low-level representation in which everything is just numbers: digital information.

Second is the *universal digital processor*. All of this digital information can be processed by a single general-purpose device, the digital computer. Digital computers that process the uniform digital representation have replaced the elaborate and complicated mechanical devices that process analog representations. As we'll see, computers are all equally capable in what they can compute, differing only in how fast they operate and how much data they can store. A smartphone is a computer of great sophistication, with as much computing power as a laptop. Thus more and more of what might once have been limited to desktop or laptop computers has found its way onto phones, and this process of convergence is accelerating.

Third is the *universal digital network*. The Internet connects the digital computers that process the digital representation; it connects computers and phones to mail, search, social networks, shopping, banking, news, entertainment, and everything else. Most of the world's population has access to this network. You can exchange email with anyone, regardless of where they might be or how they choose to access their

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

mail. You can search, comparison shop, and purchase from your phone, laptop, or tablet. Social networks keep you in touch with friends and family, again from your phone or computer. You can watch endless entertainment, often for free. "Smart" devices monitor and control systems in your home; you can talk to them to ask them questions or tell them what to do. There's a worldwide infrastructure that makes all these services work together.

Fourth, an immense amount of *digital data* is continuously being collected and analyzed. Maps, aerial photographs, and street-level views of much of the world are freely available. Search engines tirelessly scan the Internet so they can answer queries efficiently. AI agents just as tirelessly scan the Internet to scoop up any kind of information that might be useful in training models. Millions of books are available in digital form. Social networks and sharing sites maintain enormous amounts of data for and about us. Both online and brick-and-mortar stores and services provide access to their wares while quietly recording everything we do when we visit them, aided and abetted by search engines, social networks and our phones. For all of our online interactions, Internet service providers log the connections we make, and likely much more. Governments spy on us all the time, to an extent and at a level of detail that would have been impossible two or three decades ago.

All of this is changing rapidly because digital technological systems continue to get smaller, faster, cheaper and more powerful. New phones with fancier features, better screens, and more interesting applications arrive continuously. New gadgets appear all the time; the most useful find their functionality subsumed into phone apps. This is a natural by-product of digital technology, in which any technological development leads to improvement across the board for digital devices: if some change makes it possible to handle data cheaper, faster or in larger quantity, all devices will benefit. As a result, digital systems are pervasive, an integral part of our lives both visibly and behind the scenes.

This progress must surely seem like a good thing, and indeed in most ways it is. But there are ominous clouds around the silver lining. One of the most obvious and perhaps the most worrying to individuals is the impact of technology on personal privacy. When you use your phone to search for some product and then visit store web sites, all parties keep records of what you visited and what you clicked on. They know who you are because your phone identifies you uniquely. They know where you are because your phone reports its location all the time. The phone company records this information and may sell it. With GPS, the Global Positioning System, you can be located to within five to ten meters; if you enable location services on your phone, that information is available to apps, and they too can use or sell that information. In fact, it's even worse: disabling location services only prevents apps from using GPS data; it does not prevent the phone's operating system from collecting and uploading the data, which it could do by the cell network, Wi-Fi or Bluetooth.

You're being watched in real life as well as online. Face recognition technology can identify you on the street or in a store. Traffic cameras scan your license plates and know where your car is; so do electronic toll-collection systems. Internet-connected smart thermostats, voice responders, door locks, baby monitors and security cameras are surveillance devices that we have invited into our homes. The tracking

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

that we permit today without even thinking about it makes the monitoring in George Orwell's *1984* look casual and superficial.

The records of what we do and where we do it may well live forever. Digital storage is so cheap and data is so valuable that information is rarely discarded. If you post something embarrassing online or send mail that you subsequently regret, it's too late. Information about you can be combined from multiple sources to create a detailed picture of your life, and is available to commercial, government and criminal interests without your knowledge or permission. It is likely to remain available indefinitely and could surface to harm you at any time in the future.

The universal network and its universal digital information have made us vulnerable to strangers to a degree never imagined a decade or two ago. As Bruce Schneier says in his excellent book *Data and Goliath*, "Our privacy is under assault from constant surveillance. Understanding how this occurs is critical to understanding what's at stake."

The societal mechanisms that protect our privacy and our property have not kept up with the rapid advances in technology. Thirty years ago, I dealt with my local bank and other financial institutions by physical mail and occasional personal visits. Accessing my money took time and it left an extensive paper trail; it would have been difficult for someone to steal from me. Today, I am forced to deal with financial institutions mostly through the Internet. I can access my data conveniently, but it's possible that through some blunder on my part or a screwup by one of these companies, someone on the far side of the world could clean out my account, steal my identity, ruin my credit rating, and who knows what else, in no time at all and with little chance of recourse.

This book is about understanding how digital systems work and how they are changing our lives. Of necessity it's a snapshot, so you can be certain that ten years from now, today's systems will seem clunky and antiquated. Technological change is not an isolated event but an ongoing process—rapid, continuous, and accelerating. Fortunately, the basic ideas of digital systems will remain the same, so if you understand those, you'll understand tomorrow's systems too, and you'll be in a better position to deal with the challenges and the opportunities that they present.

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Part I

Hardware

"I wish to God these calculations had been executed by steam."

Charles Babbage, 1821, quoted in Harry Wilmot Buxton,
Memoir of the Life and Labours of the Late Charles Babbage, 1872.

Hardware is the solid, visible part of computing: devices and equipment that you can see and put your hands on. The history of computing devices is interesting, but I will only mention a little of it here. Some trends are worth noting, however, especially the exponential increase in how much circuitry and how many devices can be packed into a given amount of space, for a fixed price. As digital equipment has become cheaper and more powerful, widely disparate mechanical systems have been superseded by much more uniform electronic ones.

Computing machinery has a long history, though most early computational devices were specialized, often for predicting astronomical events and positions. For example, one (unproven) theory holds that Stonehenge was an astronomical observatory. The Antikythera mechanism, from about 100 BCE, is an astronomical computer of remarkable mechanical sophistication. Arithmetic devices like the abacus have been used for millennia, especially in Asia. Seventeenth century mathematicians like Pascal and Leibniz built mechanical calculators that could do basic arithmetic. The slide rule was invented in the early 1600s, not long after John Napier's description of logarithms. I used one as an undergraduate engineering student in the 1960s, but slide rules are now curiosities, replaced by calculators and computers, and my painfully acquired expertise is useless.

The most relevant precursor to today's computers is the Jacquard loom, which was invented in France by Joseph Marie Jacquard around 1800. The Jacquard loom used rectangular cards with multiple rows of holes that specified weaving patterns. The Jacquard loom thus could be "programmed" to weave a wide variety of different patterns under the control of instructions that were provided on punched cards; changing the cards caused a different pattern to be woven. The creation of these labor-saving machines for weaving led to widespread social disruption as weavers were put out of work; the Luddite movement in England in 1811–1816 was a violent

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

protest against mechanization. Modern computing technology has similarly led to disruption; for example, we are in the early stages of major changes that will be caused by artificial intelligence.

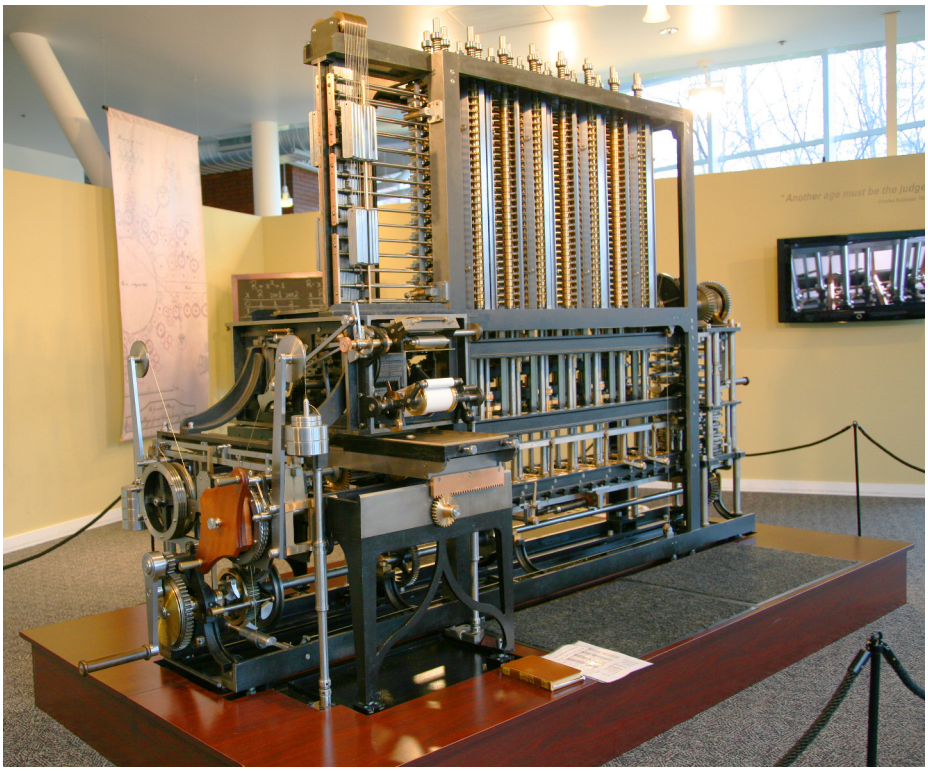

Figure I.1: Modern implementation of Babbage's Difference Engine.

Computing in today's sense began in England in the mid-19th century with the work of Charles Babbage. Babbage was a mathematician and scientist who was interested in navigation and astronomy, both of which required tables of numeric values for computing locations. Babbage spent much of his life trying to build computing devices that would mechanize the tedious and error-prone manual arithmetic calculations needed to create the tables, and even to print them. You can sense his exasperation in the quotation on the previous page. For a variety of reasons, including alienating his financial backers, he never succeeded in his ambitions, but his designs were sound. Modern implementations of some of his machines, built with tools and materials appropriate to his time, can be seen in the Science Museum in London; the version in the figure above was on display in the Computer History Museum in Mountain View, California.

Babbage encouraged a young woman, Augusta Ada Byron, the daughter of the poet George Byron, and later Countess of Lovelace, in her interests in mathematics and his computational devices. Lovelace wrote detailed explanations of the use of Babbage's Analytical Engine (the most advanced of his planned devices) for

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Figure I.2: Ada Lovelace. Detail from 1836 portrait by Margaret Sarah Carpenter.

scientific computation and speculated that machines could do non-numeric computation as well, such as composing music.

> Supposing, for instance, that the fundamental relations of pitched sounds in the science of harmony and of musical composition were susceptible of such expression and adaptations, the engine might compose elaborate and scientific pieces of music of any degree of complexity or extent.

Ada Lovelace is sometimes called the world's first programmer, perhaps an overstatement, but she definitely saw more clearly than others the potential of computing devices to do more than crunch numbers. The Ada programming language is named in her honor.

Herman Hollerith, working with the US Census Bureau in the late 1800s, designed and built machines that could tabulate census information far more rapidly and reliably than could be done by hand. Using ideas from the Jacquard loom, Hollerith used holes punched in stiff paper cards to encode census data in a form that could be processed by his machines. Famously, the 1880 census had taken eight years to tabulate, but with Hollerith's punch cards and tabulating machines, the 1890 census results took only one year to prepare, instead of the predicted 10 years or more. Hollerith founded a company that in 1924 became, through mergers and acquisitions, International Business Machines, which we know today as IBM.

Babbage's machines were complex mechanical assemblies of gears, wheels, levers and rods. The development of electronics in the 20th century made it possible to imagine computers that did not rely on mechanical components. The first significant one of these all-electronic machines in the US was ENIAC, the Electronic Numerical Integrator and Computer, which was built from 1944 to 1946 at the University of Pennsylvania in Philadelphia, by Presper Eckert and John Mauchly. ENIAC occupied a large room and required 140 kilowatts of electric power, enough

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

to power 100 homes; it could do about 5,000 additions in a second. It was intended to be used for ballistics computations and the like, but it was not completed until well after the end of World War II. (Parts of ENIAC are on display in the Moore School of Engineering at the University of Pennsylvania.)

Babbage saw clearly that a computing device could store its operating instructions and its data in the same form, which is the insight that makes modern computing possible. But ENIAC did not store instructions in memory along with data; instead it was programmed by a slow and tedious process of setting up connections through switches and re-cabling. The first computers that truly stored programs and data together were built in England, notably EDSAC, the Electronic Delay Storage Automatic Calculator, at the University of Cambridge in 1949.

Early electronic computers used vacuum tubes as computing elements. Vacuum tubes are electronic devices roughly the size and shape of a cylindrical light bulb (see Figure 1.7 in the next chapter); they were expensive, fragile, bulky, and power hungry. With the invention of the transistor in 1947, and then of integrated circuits in 1958, the modern era of computing really began. These technologies have allowed electronic systems to steadily become smaller, cheaper and faster.

The next three chapters describe computer hardware, focusing more on the logical architecture of computing systems than on the physical details of how they are built. The basic architecture has been largely unchanged for decades, while the hardware implementation has changed to an astonishing degree. The first chapter is an overview of the structure and components of a computer. The second chapter shows how computers represent information with bits, bytes and binary numbers. The third chapter explains how computers actually compute: how they process the bits and bytes to make things happen.

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

1

What Is a Computer?

> "Inasmuch as the completed device will be a general-purpose computing machine it should contain certain main organs relating to arithmetic, memory-storage, control and connection with the human operator."
>
> Arthur W. Burks, Herman H. Goldstine, John von Neumann, "Preliminary discussion of the logical design of an electronic computing instrument," 1946.

Let's begin our discussion of hardware with an overview of what a computer is. We can look at a computer from at least two viewpoints: the logical or functional organization—what the pieces are, what they do and how they are connected—and the physical structure—what the pieces look like and how they are built. The goal of this chapter is to understand what a computer is, see what's inside, learn what each part does, and get a sense of what the myriad acronyms and numbers mean.

Think about your own computing devices. Many readers will have some kind of "PC," that is, a laptop or desktop computer descended from the Personal Computer that IBM first sold in 1981, running some version of the Windows operating system from Microsoft. Others will have an Apple Macintosh that runs a version of the macOS operating system. Still others might have a Chromebook running ChromeOS that relies on the Internet for most of its storage and computation. More specialized devices like smartphones, tablets and ebook readers are also powerful computers. These all look different and when you use them they feel different as well, but underneath the skin, they are fundamentally the same. We'll talk about why.

There's a loose analogy to cars. Functionally, cars have been the same for well over a hundred years. A car has an engine that uses some kind of fuel or energy source to make the engine run and the car move. It has a steering wheel that the driver uses to control the car. There are places to store the fuel and places to store the passengers and their goods. Physically, however, cars have changed greatly over a century: they are made of different materials, and they are faster, safer, and much more reliable and comfortable. Their propulsion systems may be electric motors instead of internal combustion engines. There's a world of difference between my first car, a well-used 1959 Volkswagen Beetle, and a Ferrari, but either one will carry

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

me and my groceries home from the store or across the country, and in that sense they are functionally the same. (For the record, I have never even sat in a Ferrari, let alone owned one, so I'm speculating about whether there's room for the groceries. I did park next to one once—Figure 1.1.)

Figure 1.1: The closest I've ever come to a Ferrari.

The same is true of computers. Logically, today's computers are very similar to those of the 1950s, but the physical differences go far beyond the kinds of changes that have occurred with the automobile. Today's computers are much smaller, cheaper, faster and more reliable than those of 75 years ago, easily a million or even a billion times better in some properties. Such improvements are the fundamental reason why computers are so pervasive.

The distinction between the functional behavior of something and its physical properties—the difference between what it does and how it's built or works inside—is important. For computers, the "how it's built" part changes at an amazing rate, as does how fast it runs, but the "what it does" part is quite stable. This distinction between an abstract description and a concrete implementation will come up repeatedly in what follows.

I sometimes do a survey in my class in the first lecture. How many have a PC? How many have a Mac? The ratio was fairly constant at 10 to 1 in favor of PCs in the early 2000s, but changed rapidly over a few years, and for the past twenty years Macs have accounted for well over three quarters of the computers. This is not typical of the rest of world, however, where PCs are likely to dominate.

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Is the ratio unbalanced because one is superior to the other? If so, what changed so dramatically in such a short time? I ask my students which kind is better, and for objective criteria on which to base that opinion. What led you to your choice when you bought your computer?

Naturally, price is one answer. PCs tend to be cheaper, the result of fierce competition in a marketplace with many suppliers. A wider range of hardware add-ons, more software, and more expertise are all readily available. This is an example of what economists call a *network effect*: the more other people use something, the more useful it will be for you, roughly in proportion to how many others there are.

On the Mac side are perceived reliability, quality, esthetics, and a sense that "things just work," for which many consumers are willing to pay a premium.

The debate goes on, with neither side convincing the other, but it raises some good questions and helps to get people thinking about what is different between various kinds of computing devices and what is really the same.

There's an analogous debate about phones. Almost everyone has a "smartphone" that can run programs ("apps") downloaded from Apple's App Store or the Google Play Store. The phone serves as a browser, a mail system, a watch, a camera, a music and video player, a voice recorder, a map, a navigator, a comparison shopping tool, and even occasionally as a device for conversation. Typically more than three quarters of my students have iPhones; the rest have Android phones from one of many suppliers. iPhones are more expensive but offer smooth integration with Apple's ecosystem of computers, tablets, watches, music players, accessories, and cloud services, another example of a network effect. Rarely, someone admits to having only a "feature phone," which is defined as a phone that has no features beyond the ability to make phone calls. My sample is for the US and a comparatively affluent environment; in other environments and other parts of the world, Android phones would be much more common.

Again, people have good reasons—functional, economic, social, esthetic—for choosing one kind of phone over others but underneath, just as for PCs versus Macs, the hardware that does the computing is very similar. Let's look at why.

1.1 Logical Construction

If we were to draw an abstract picture of a simple generic computer—its logical or functional architecture—it would look like the diagram in Figure 1.2 for both a Mac and a PC: a processor, some primary memory, some secondary storage, and a variety of other components, all connected by a set of wires called a *bus* that carries information between them.

If instead we drew this picture for a phone or tablet, it would be similar, though mouse, keyboard and display are combined into one component, the screen, and there are hidden components like a compass, an accelerometer, and a GPS receiver for determining your physical location.

The basic organization—a processor, memory and storage for instructions and data, and input and output devices—has been standard since the 1940s. It's called the *von Neumann architecture*, after John von Neumann, who described it in the 1946 paper quoted above. Though there is still occasional debate over whether von

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

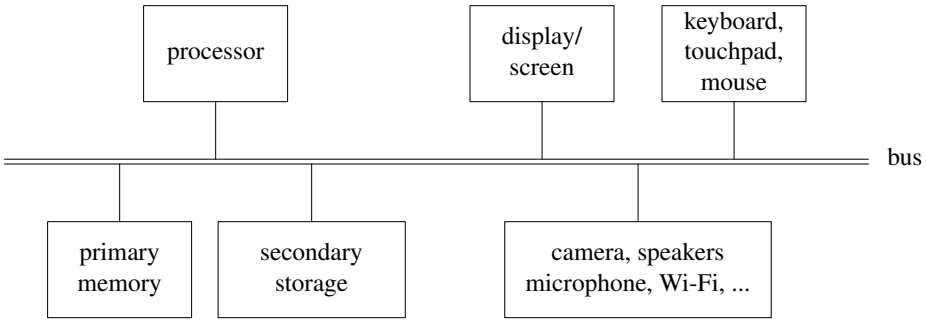

Figure 1.2: Architectural diagram of a simple idealized computer.

Neumann gets too much credit for ideas that originated with others, the paper is so clear and insightful that it is well worth reading even today. For example, the quotation at the beginning of this chapter is the first sentence of the paper. Translated into today's terminology, the processor provides arithmetic and control, the primary memory and secondary storage are memory-storage, and the keyboard, mouse and display interact with the human operator.

A note on terminology: the processor has historically been called the *CPU* or *central processing unit*, but is now more often simply "processor." The primary memory is called *RAM* or *random access memory*, and secondary storage is *disk* or *drive*, reflecting different physical implementations. I'll mostly use the words processor, memory and storage, but with occasional lapses into the older terms.

1.1.1 Processor

The processor is the brain, if a computer could be said to have such a thing. The processor does arithmetic, moves data around, and controls the operation of the other components. The processor has a limited repertoire of basic operations that it can perform but it does them blazingly fast, billions per second. It can decide what operations to do next based on the results of previous computations, so it is to a considerable degree independent of its human users. We will spend more time on this component in Chapter 3 because it's so important.

If you go to a store or shop online to buy a computer, you'll find most of these components mentioned, usually accompanied by mysterious acronyms and equally mysterious numbers. For example, you might see a processor described as a "2.2 GHz dual-core Intel Core i7," as it is for one of my older computers. What's that? Intel makes the processor and "Core i7" is Intel's trademarked name for an extensive line of processors. This particular processor has two processing units in a single package; in this context, lower case "core" has become a synonym for "processor." A core is a processor in its own right, but the CPU may have several cores that can work together or independently to compute faster. For most purposes, however, it's sufficient to think of the combination as "the processor," no matter how many cores it might have.

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

"2.2 GHz" is the more interesting part. Processor speed is measured, at least approximately, in terms of the number of operations or instructions or parts thereof that it can do in a second. The processor uses an internal clock, rather like a heartbeat or the ticking of a clock, to step through its basic operations. One measure of speed is the number of such ticks per second. One beat or tick per second is called one *hertz* (abbreviated *Hz*), after the German engineer Heinrich Hertz, whose 1888 discovery of how to produce electromagnetic radiation led directly to radio and other wireless systems. Computers of the 1970s had clock speeds measured in millions of ticks per second, or megahertz, or MHz. Computers today typically run at billions of hertz, or gigahertz, or GHz; my quite ordinary 2.2 GHz processor is zipping along at 2,200,000,000 ticks per second. The human heartbeat is around 1 Hz or almost 100,000 beats per day, which is around 30 million per year. So each core in my processor does in 1 second the number of beats my heart would do in 70 years.

This is our first encounter with some of the numerical prefixes like mega and giga that are so common in computing. "Mega" is one million, or 10^6; "giga" is one billion, or 10^9, and pronounced with a hard "g" as in "gig." We'll see more units soon enough, and there is a complete table at the beginning of the glossary.

1.1.2 Primary memory

The primary memory stores information that is in active use by the processor and other parts of the computer; its contents can be changed by the processor. The primary memory stores not only the data that the processor is currently working on, but also the instructions that tell the processor what to do with that data. This is a crucially important point: by loading different instructions into memory, we can make the processor do a different computation. This makes the stored-program computer a general-purpose device. The same computer can run a word processor and a spreadsheet, surf the web, send and receive email, keep up with friends on Instagram, do your taxes, and play music, all by placing suitable instructions in the memory. The importance of the stored-program idea cannot be overstated.

The primary memory provides a place to store information while the computer is running. It stores the instructions of programs that are currently active, like Word, Photoshop or a browser. It stores their data—the documents being edited, the pictures on the screen, the music that's currently playing. It also stores the instructions of the operating system—Windows, macOS or something else—that operates behind the scenes to let you run multiple applications at the same time. We'll talk about applications and operating systems in Chapter 6.

The primary memory is called *random access* because the processor can access the information stored at any place within it as quickly as in any other; to over-simplify a little, there's no speed penalty for accessing memory locations in any particular order. Though they passed from the scene long ago, you might remember VCR tapes, where to watch the end of a movie, you had to fast-forward (slowly!) over everything from the beginning; that's called *sequential access*.

Most RAM is *volatile*, that is, its contents disappear if the power is turned off, and all of the currently active information is lost. That's why it's prudent to save your work often, especially on a desktop machine, where tripping over the power cord

(continued...)

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Index

"Any inaccuracies in this index may be explained by the fact that it has been sorted with the help of a computer."

Donald E. Knuth, *The Art of Computer Programming*, Volume 3, *Searching and Sorting*, 1973.

1-click patent, Amazon 91
1Password 205
3-2-1 backup strategy 206
3Com 150
3G cell phone 155
4G, 5G cell phone 157, 282
64-bit memory address 40
802.11 wireless standard 152, 157, 162, 282

abstraction 12, 18, 101, 106, 113, 117, 140, 268
accumulator 44, 51, 53
acknowledgment, TCP 176
active content 193
Activity Monitor, macOS 101
Ad Exchange, Google 218
Ada Lovelace 8–9
Ada programming language 9
address translation (NAT), network 169
address, Ethernet 150
 IP 165, 168, 285
 IPv4 165
 IPv6 165, 169
Adleman, Leonard 254
Advanced Audio Coding (AAC) 33, 160, 282
advertising, Google 271
AES encryption standard 252, 282
Afghanistan Internet shutdown 208
age verification 271
AI winter 235
Aiken, Howard 80
airplanes, computers in 60
Akamai 175
`alert` function 123, 129
Alexa 233
algorithm complexity 71, 139, 283
algorithm complexity graph 69, 133
algorithm vs program 75
algorithm, ATM checksum 161
 binary search 66, 282
 definition of 64, 139, 282
 divide and conquer 66, 68, 169
 exponential 71, 254, 284
 ISBN checksum 161
 linear 65
 MD5 message digest 256, 285
 N log *N* 69
 PageRank 214
 quadratic 68–69, 286
 Quicksort 68, 91
 recipe as 63
 `rot13` encryption 250
 RSA public-key 254, 286
 selection sort 67
 SHA-3 message digest 256, 286
 tax form as 63
Allen, Paul 80
allocation, spectrum 152, 162
AlphaGo, AlphaZero 240
Altair computer 80
AltaVista search engine 212
Alto computer 149
Amazon xiii, 122, 167, 177, 192, 255, 271
Amazon 1-click patent 91
Amazon Echo 221
Amazon Fire TV 221
Amazon Kindle 93, 101, 108
Amazon Ring 246, 270
Amazon transparency report 230
Amazon Web Services (AWS) 104
AMD processor 52
amplitude modulation (AM) 151, 282
AMSL 23
analog hole 90
analog vs digital 27
analog watch 28
analog-digital conversion 29
Android operating system 96
Android phone 13, 94, 101, 107
Android SDK 86
Android Studio IDE 86
Anguilla, `.ai` 168
Anna Kournikova virus 195–196
anonymizing data 226
Anthropic 90, 183, 234
anti-virus software 206
Antikythera mechanism 7
AOL query logs 226
Apache web server 96
app 13, 99, 115, 282
Apple 11, 86, 91, 99, 101, 117
Apple AirTag 152
Apple iCloud 264
Apple Neo 52
Apple Time Machine 206
Apple TV 221
Application Programming Interface (API) 86, 93, 122, 128, 140, 223, 282
application, `date` 115
application-level protocol 174
architecture, instruction set 51
architecture, von Neumann 13, 24
arithmetic, binary 38
ARM processor 52, 77, 117, 282
ARPANET 163–164
ASCII characters, table of 34
ASCII standard 34, 40, 57, 95, 158, 178, 282
ASCII with parity, table of 161
assembler 76, 139, 282
assembly programming language 76
assignment statement 125–126
asynchronous event 116
AT&T 144–145, 153, 231
ATM checksum algorithm 161
attack, brute force 204, 252
 dictionary 195, 252
 escalation of privilege 200
 man-in-the-middle 143, 155, 203, 250, 253, 285

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

phishing xii, 198, 286
SIM-swapping 201
social engineering 197, 199, 287
spear phishing 199, 286
SQL injection 202
supply-chain 61
zero-day 88
attention mechanism 243
Austen, Jane 136
authentication, key 255
password 178, 185, 191, 200, 203–204, 265
two-factor 205
Authors Guild vs Google 182
autonomous system 171
Autopilot, Tesla 60, 93
autorun 196

Babbage, Charles 7–8
backdoor, cryptographic xiii, 252, 264, 282
backup strategy, 3-2-1 206
Backus, John 79
bandwidth 147–148, 157, 282
barcode 18, 161
Bardeen, John 20
base 2 logarithm 66
base station, cell phone 153
base station, wireless 151, 282
BASIC programming language 80
Bell Labs 20, 80, 100, 144
Bell, Alexander Graham 143, 147
Bengio, Yoshua 239
Berners-Lee, Tim 188
best effort 175
Betamax vs VHS 94
Bezos, Jeff 91, 207
big data 225
bigit 35
binary addition table 39
binary arithmetic 38
binary digit 35
binary multiplication table 39
binary numbers 37, 57, 282
binary search algorithm 66, 282
binary to decimal conversion 38
Bing search engine 74, 189
bit rot 88, 282
bit, origin of 27, 35
Bitcoin blockchain 262, 282
Bitcoin protocol 181, 201, 261, 282
bits, meaning of 35, 37, 282
BitTorrent protocol 181, 282
Blacklight tracker monitor 221
block, disk 110
Blu-ray vs HD-DVD 94
blue screen of death 101
Bluetooth 108, 152, 282
Boeing 737 MAX 60
Boeing MCAS 60
Boggs, David 149
booting 105
bot, botnet 200, 282
branch instruction 47
branch instruction, conditional 47
Branwen, Gwern 246
Brattain, Walter 20
breach, Capital Health 202
Equifax 202
RSA 205
SecurID 205
TransUnion 202
UnitedHealthcare 61, 202
VPN 204
bricking 183, 282
Brin, Sergey 212
broadcast network 147, 186
Brooks, Frederick P. 99–100
browser fingerprinting 220, 258
browser, Chrome 81, 116, 123, 188
Chromium 96
DuckDuckGo 206
Edge 116, 188
Firefox 81, 96, 116, 123, 188, 206, 259
Internet Explorer 118, 188
Mosaic 188
Netscape Navigator 118, 188, 193
Safari 116, 123, 188, 204
Tor 207, 259
browserleaks.com 220
brute force attack 204, 252
Buchholz, Werner 39
bug 86, 128–129, 140, 195, 283
bug picture 86
Burks, Arthur 11, 43, 53
bus 13, 18, 283
Butler, Samuel 1
byte 16, 39, 283
`bzip2` compression 158

C programming language 80–81, 83, 95, 116, 193
C# programming language 96
C++ programming language 80–81, 83, 95, 116
cable modem 148, 151, 283
cache 51, 53, 169, 283
Caesar cipher 250
California Consumer Privacy Act (CCPA) 222
California Delete Request and Opt-out Platform (DROP) 222
canvas fingerprinting 220
Capital Health breach 202
CAPTCHA 55, 283
cars, computers in 59
Cascading Style Sheets (CSS) 191
CD encoding 32
CD-ROM 32, 113
cell phone base station 153
cell phone cells diagram 154
cell phone frequency 154
cell phone, 3G 155
cell phone, 4G, 5G 157, 282
central processing unit (CPU) 14, 43, 283, 286
Cerf, Vinton 177
CERN 188
certificate 257, 283
certificate authority 257
Chappe, Claude 142
chatbot, Eliza 241
ChatGPT xiii, xv–xvi, 1, 90, 234, 241
checksum algorithm, ATM 161
checksum algorithm, ISBN 161
chess 233, 240
Children's Online Privacy Protection Act (COPPA) 184
chip 21, 283
Chrome browser 81, 116, 123, 188
Chromebook 11, 116
Chromecast 221
ChromeOS operating system 11, 116, 283
Chromium browser 96
circuit board 19
Claude xvi, 234, 242
Clay Mathematics Institute 73
cleanroom development 90, 103
Clearview AI 240
client-server 181, 187, 191, 283, 286
cloud computing xiii, 25, 104, 114, 227, 283
cloud picture 227
clustering, *k*-means 237
coaxial cable 151
COBOL programming language 79
Cocks, Clifford 254
code size, Google 85
Codecademy 122
Cohen, Bram 181
Coinbase 263
Colab, Google 122, 130, 136
color representation, RGB 30, 40, 286
Comcast 145
command, `nslookup` 169
`telnet` 178
`traceroute` 172
`whois` 168
comments 46
Communications Decency Act 145
compact disc 32
compilation process diagram 78
compiler 77, 129, 136, 139, 283
complexity graph, algorithm 69, 133
complexity, algorithm 71, 139, 283
components, software 85
compression, `bzip2` 158
data 155, 158, 229, 283
GIF 158, 191, 284
Huffman code 158
JPEG 33, 74, 159, 191, 283, 285
lossless 158
lossy 159
MP3 17, 33, 74, 160, 180, 283, 285
MPEG 33, 74, 159, 285
PNG 74, 158, 286
ZIP 74, 158
computer architecture 51
computer architecture diagram 13
Computer Fraud and Abuse Act 195
computer vision 239
computer, Altair 80
Alto 149
EDSAC 10, 76
ENIAC 9, 20
IBM 7094 xi
IBM PC 11, 23
stored-program 15, 55
Toy 44, 76
computers in airplanes 60
computers in cars 59
computers in medical imaging 61
computers in voting machines 61
concatenation, text 125, 127
conditional branch instruction 47
Confucius 121
conversion, analog-digital 29
binary to decimal 38
decimal to binary 38
Cook, Stephen 72
Cook, Tim 264
cookie 192, 217, 283
cookie, third-party 197, 206
cookies, tracking 192, 217
cooking robot 75
copyright 89, 95, 181
copyright lifetime 90, 270
Count of Monte Cristo 143
CoverYourTracks 221, 260
Covid-19 61, 235

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

crawl, crawler 212
Creative Commons license 96
cryptocurrency 262, 283
cryptographic backdoor xiii, 252, 264, 282
cryptographic hash 256
cryptographic key 251
cryptography 71, 74, 250
`ctof` function 87
CTSS operating system 100
cyber attack, Ukraine 61
cyber warfare 61, 196, 270

dark web 283
data compression 155, 158, 229, 283
Data General Corporation 100
data mining 209
data science 209
data structure 64, 82, 86
`date` application 115
DDoS *see* denial of service attack
debugging 86, 88, 128
decimal to binary conversion 38
declaration, variable 124, 126, 283, 287
deep learning 234, 283
deep packet inspection 221
definition of algorithm 64, 139, 282
deidentification 226
delay 147
denial of service attack (DDoS) 203
Dept of Justice vs Microsoft 118, 188
DES encryption standard 252, 283
device driver 107, 283
DHCP protocol 166
diagram, cell phone cells 154
 compilation process 78
 computer architecture 13
 Ethernet packet 150
 file system organization 110
 IPv4 packet 175
 operating system and libraries 107
 protocol layers 174
 search engine 212
 sound wave 31
 TCP segment 176
 TCP/IP connection 177
 Toy program in memory 49
 virtual operating system 104
dictionary attack 195, 252
Diffie, Whitfield 253
Digital Equipment Corporation (DEC) 100
Digital Millennium Copyright Act (DMCA) 182–183, 283
digital representation 32
digital rights management (DRM) 90
digital signature 255
digital television 162
digital vs analog 27
digital watch 28
directory *see* folder
disc, compact 32
disk block 110
disk, floppy 23
distributed computing 54
divide and conquer algorithm 66, 68, 169
division by zero 65, 128
DMCA safe harbor 182
Do Not Track 218
DOGE xii, 264, 270
domain name 166, 189, 283
domain name registrar 167, 170, 286
Domain Name System (DNS) 166–167, 174, 283
domain name, internationalized 168
domain name, Unicode 168
domain, top-level 167
DoS *see* denial of service attack
dotted decimal notation 165
DoubleClick 218
doxx, doxxing 283
Dropbox 114, 227
DSL 284
DuckDuckGo browser 206
DuckDuckGo search engine 215
Dumas, Alexandre 143
dumb network 185
DVD 32, 40, 113
Dynamic Host Configuration Protocol (DHCP) 166

eavesdropping 186, 254
echo chamber 207
Eckert, J. Presper 9
Edge browser 116, 188
Edison, Thomas 30, 86
EDSAC computer 10, 76
Eich, Brendan 82, 193
electrical telegraph 143
Electronic Frontier Foundation (EFF) 221
Eliza chatbot 241
Ellis, James 254
email privacy 230
embedded system 59, 81
embedding 242
encoding, CD 32
 Punycode 170
 RBG 40
 URL 189
 UTF-8 58, 287
encryption 90, 148, 150, 207
encryption (WEP, WPA), wireless 162
encryption algorithm, `rot13` 250
encryption standard, AES 252, 282
encryption standard, DES 252, 283
encryption, end-to-end 204, 264
encryption, iPhone 264
end-to-end encryption 204, 264
end-to-end principle 185
English wine measures 41
ENIAC computer 9, 20
Enigma 55, 251
Equifax breach 202
error correction 74, 114, 155, 160
error detection 160
error, semantic 79
error, syntax 78
escalation of privilege attack 200
Ethernet 149, 284
Ethernet address 150
Ethernet packet 165
Ethernet packet diagram 150
Ethernet range 151
EULA 92, 284
European Union xiii, 222, 229, 271
exa 54, 209
exchange point (IXP), Internet 171, 285
expert system 235
exponential algorithm 71, 254, 284
extension, Ghostery 206, 217, 231
 NoScript 194, 207
 Privacy Badger 206
 uBlock Origin 206, 231

F# programming language 96
face recognition 3, 234, 239
Facebook xii, 122, 145, 167, 211, 222–223, 271
Facebook Like 224
Facebook transparency report 230
factoring 254
factoring challenge, RSA 254
Fanning, Shawn 180
feature phone 13
features, machine learning 239
Federal Communications Commission (FCC) 145, 152
Federal Election Commission (FEC) 225
Federal Trade Commission (FTC) 183, 204
fetch-decode-execute cycle 44, 50
Feynman Algorithm 63
fiber, optical 22, 144, 147, 149, 157, 163, 284
File Recovery program, Windows 112
file sharing 180
file system 17, 108, 284
file system organization diagram 110
file system, network 114
 RAID 114
 SD card 113
 USB 113
filter bubble 207, 284
fingerprinting, browser 220, 258
fingerprinting, canvas 220
Firefox browser 81, 96, 116, 123, 188, 206, 259
firewall 207–208, 272, 284
firkin 41
first sale doctrine 93
flash memory 16, 113, 284
flicker 33
floating-point operation (flop) 54
Flock surveillance 270
floppy disk 23
floppy disk virus 196
folder 109, 284
folder contents 110
folder, trash 112
`for` loop, Python 133
`form` tag 191
form, HTML 191
Fortran programming language 79
forward secrecy 256
Fox News 2
Frankenpine 155
Free Software Foundation 95
frequency modulation (FM) 151, 284
frequency, cell phone 154
`ftoc` function 87
function 85
function call 85, 284
function, `alert` 123, 129
 `ctof` 87
 `ftoc` 87
 `parseInt` 127
 `prompt` 124–125, 129

Gates, Bill 80
gateway 164–166, 171–172, 175, 177, 185, 221, 284
gateway vs router 164
Gell-Mann, Murray 63
Gemini xvi, 136, 234
General Data Protection Regulation (GDPR) xiii, 222, 284
Generative Pre-trained Transformer (GPT) 243, 284
geo-tagging 216
geolocation 223
Ghostery extension 206, 217, 231
GIF compression 158, 191, 284

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

giga 15, 281
GitHub 136
Global Positioning System (GPS) 5, 153, 216, 284
Gmail 180, 227
GNU General Public License (GPL) 95–96, 284
GNU project 95
Go (game) 233, 240
Go programming language 96
Goldstine, Herman 11, 43, 53
Google xiii, 96, 116, 122, 153, 167, 212, 234
Google Ad Exchange 218
Google Ads 214
Google advertising 271
Google Cloud Platform 104
Google code size 85
Google Colab 122, 130, 136
Google Docs 114, 122, 228
Google Drive 114
Google Maps 128, 140
Google Meet 144
Google search engine 74
Google Sheets 114
Google Street View 239
Google tag manager 219
Google Takeout 206
Google transparency report 230
Gosling, James 81
`GOTO` instruction 47, 126
Government Communications Headquarters (GCHQ) 254
graph, algorithm complexity 69, 133
Graphics Processing Unit (GPU) 23, 52, 253, 284
grayscale 40
Great Firewall of China 208, 222
GSM 284
Gutenberg Project 136

Hacker News 2
hallucination 244
hard disk, hard drive 16, 284
Harvard Mark I, II 80, 86
hash, cryptographic 256
haveibeenpwned.com 205
HD-DVD vs Blu-ray 94
Hellman, Martin 253
Herodotus 142
hertz (Hz) 15, 151
Hertz, Heinrich 15
hexadecimal 39, 150, 165, 189, 284
high-level programming language 77
Hinton, Geoffrey 239
Hoare, Tony 68
Hollerith, Herman 9
Hopper, Grace 79, 86, 157
host 170
hotspot, mobile 156
HP printers 183
HTML 122–123, 187, 189, 284
HTML form 191
HTML tag 189
HTML5 220
HTTP protocol 177, 187, 284
HTTPS protocol 177, 189, 203, 206, 222, 255, 284
Huffman code compression 158
hypertext 188

IBM 9, 39, 79, 96, 100, 117, 161, 167, 252
IBM 7094 computer xi
IBM OS/360 operating system 100
IBM PC computer 11, 23
IBM System/360 100
ICANN 167, 170, 284
iCloud, Apple 264
IEEE 152
`if-else` statement 127
`ifconfig`, `ipconfig` 150
`IFZERO` instruction 47, 126–127
image recognition 239
IMAP protocol 180
iMessage 204
`img` tag 190
Immigration and Customs Enforcement (ICE) 3
`import`, Python 133
in-store beacon 223
incognito mode 219
infrared 151
Instagram xii, 211, 223–224, 271
instruction repertoire 44, 51
instruction set architecture 51
instruction, branch 47
  conditional branch 47
  `GOTO` 47, 126
  `IFZERO` 47, 126–127
  jump 47
instructions, numeric values of 49
integrated circuit (IC) 10, 21, 284
integrated circuit wafer 21
Intel 22
Intel processor 14, 51, 76, 117
intellectual property 89, 284
interface 140, 285
International Mobile Equipment Identity (IMEI) 154
International System of Units (SI) 209, 281
International Telecommunication Union (ITU) 152, 164, 211
internationalized domain name 168
Internet Engineering Task Force (IETF) 167
Internet exchange point (IXP) 171, 285
Internet Explorer browser 118, 188
Internet of Things (IoT) xiii, 54, 108, 183–184, 207, 269
Internet Protocol (IP) 174, 285
Internet Service Provider (ISP) 157, 165, 171, 182, 221, 230, 258, 285
Internet shutdown, Afghanistan 208
Internet time 180
Internet voting 61
interpreter 140, 285
interpreter, Visual Basic 196
iOS operating system 101
IP address 165, 168, 285
IP packet 165
iPad 18
iPhone 13, 99, 101
iPhone encryption 264
iPhone SDK 86
IPv4 address 165
IPv4 packet diagram 175
IPv4 protocol 165
IPv6 address 165, 169
IPv6 protocol 165
ISBN checksum algorithm 161
iTunes Store 91, 99

Jacquard loom 7
Java programming language 81, 121, 193
JavaScript in PDF 195
JavaScript programming language 82, 121, 193, 228, 285
JavaScript tracking 219
jitter 147
John Deere 183
JPEG compression 33, 74, 159, 191, 283, 285
jump instruction 47
Jupyter notebook 130
jurisdiction 208, 271

k-means clustering 237
Kahn, Robert 177
kernel 117, 285
Keurig 183
key authentication 255
key distribution 253–254
key logger 200, 285
key, cryptographic 251
Khan Academy 122
Kilby, Jack 21
kilderkin 41
kilo 23, 37, 281
Kindle, Amazon 93, 101, 108
King Charles III 178
Knuth, Donald 41, 289

Large Language Model (LLM) xiii, xv–xvi, 90, 136, 241
laser 22, 32, 91
LastPass 205
latency 147
layers, software 174
LeCun, Yann 239
Leibniz, Gottfried Wilhelm 37, 39, 41
Let's Encrypt 258
library, program 86, 123, 128, 140, 285
LibreOffice 228
license 92
license, Creative Commons 96
license, virtual machine 105
LiDAR 60
linear algorithm 65
link rot 285
LinkedIn xii, 211, 224, 227
Linux operating system 96, 103, 117, 285
list, Python 133
location privacy 223
LockBit 202
logarithm 7, 66
logarithm, base 2 66
logic gate 20
long-playing record (LP) 30, 32
loop 47, 50, 53, 175, 285
loop, `while` 126
lossless compression 158
lossy compression 159
Lovelace, Ada 8–9
Luhn, Peter 161

machine learning 197, 234, 236
machine learning features 239
macOS Activity Monitor 101
macOS operating system 11, 92, 101
mailinator.com 207
malware 196, 198, 285
man-in-the-middle attack 143, 155, 203, 250, 253, 285
Mars Climate Orbiter 84
Mary, Queen of Scots 250
`matplotlib`, Python 133
Mauchly, John 9
MCAS, Boeing 60
McClure, Robert 59
McKenzie, Archie 1
MD5 message digest algorithm 256, 285
meaning of bits 35, 37, 282

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

medical imaging, computers in 61
mega 15, 281
megapixel 30
memory (RAM), random access 15, 43, 286
memory address, 64-bit 40
memory, flash 16, 113, 284
memory, virtual 101, 140, 287
Menabrea, Luigi 9
Merkle, Ralph 253
message digest algorithm, MD5 256, 285
message digest algorithm, SHA-1, SHA-2, SHA-3 256, 286
Messenger 204
metadata 3, 180, 206, 222, 224, 264
Metcalfe, Robert 149–150
micro 23, 281
microchip 21, 285
micron 23
Microsoft 11, 80, 100, 105, 188, 228
Microsoft antitrust case 118, 188
Microsoft Azure 104
Microsoft OneDrive 114
Microsoft security laws 194
Microsoft Teams 144
milli 23, 281
MIME 178
Minsky, Marvin 235
mobile hotspot 156
Mobile Virtual Network Operator (MVNO) 155
modem 148, 157, 285
modem, cable 148, 151, 283
modulation 148–149, 151
Moldova, `.md` 168
Moore's Law 22, 24, 57
Moore, Gordon 22
Morris worm 195
Morris, Robert T. 195
Morse code 158
Morse, Samuel 143
Mosaic browser 188
MP3 compression 17, 33, 74, 160, 180, 283, 285
MPAA 181
MPEG compression 33, 74, 159, 285
MS-DOS operating system 113
Multics operating system 100
Musk, Elon xii, 184, 264, 270
Muybridge, Eadweard 33

N log *N* algorithm 69
Nakamoto, Satoshi 261
name server 170
name server, root 169
nano 23, 51, 281
Napier, John 7
Napster 180
National Institute of Standards and Technology (NIST) 236, 252, 256
National Security Agency (NSA) xii, 3, 88, 165, 197, 222, 224, 252, 256, 260, 264
Near field communication (NFC) 153, 285
nearest-neighbor tour 72
negative acknowledgment 176
Nelson, Ted 188
Nest thermostat 101
net neutrality 145, 285
Netflix 17, 33, 104, 145, 181, 218
Netscape 82, 192
Netscape Navigator browser 118, 188, 193
network address translation (NAT) 169
network effect 13, 271
network file system 114
neural network 234, 285
Neural Processing Unit (NPU) 52
New York City taxi dataset 226
New York Times 90, 153, 216, 219, 224
NGINX web server 96
Nietzsche, Friedrich 211
Nigerian scam letter 198
Nobel Prize 20–21, 56, 63, 239
NoScript extension 194, 207
Notepad 124
Noyce, Robert 21
NP problem 71
`nslookup` command 169
numbers, binary 37, 57, 282
numeric values of instructions 49
Nvidia 23

object code 95, 193, 285
Objective-C programming language 81
onion router 259
open relay 186
open source 95, 285
OpenAI 1, 90, 234
OpenPGP 261
operating system 99
operating system and libraries diagram 107
operating system, Android 96
ChromeOS 11, 116, 283
CTSS 100
IBM OS/360 100
iOS 101
Linux 96, 103, 117, 285
macOS 11, 92, 101
MS-DOS 113
Multics 100
TAILS 261
Unix 100–101, 103, 115, 117, 287
virtual 104
Windows 11, 40, 100, 103, 105, 107, 117, 195–196, 198, 228
optical fiber 22, 144, 147, 149, 157, 163, 284
optical telegraph 142
Oracle vs Google 94
origin of *bit* 27, 35
Orwell, George, *1984* 6, 93
Outlook 180
Outlook.com 227

P=NP problem 73
packet 150, 165, 184, 285
packet, Ethernet 165
packet, IP 165
Page, Larry 212
PageRank algorithm 214
Panopticlick 221, 258
Parallels virtual operating system 104
PARC, Xerox 149
parity code 161
`parseInt` function 127
password authentication 178, 185, 191, 200, 203–204, 265
password manager 205
patent 91, 164, 271
patent troll 91
patent, Amazon 1-click 91
Patriot Act 224, 229
PC *see* IBM PC computer
PDF, JavaScript in 195
peer-to-peer 181, 262, 286
personally identifiable information 4, 202, 216, 222, 224, 226
peta 36, 54, 281
phishing attack xii, 198, 286
phone, feature 13
phonograph 30–31
picture, cloud 227
pipelining 51
pixel 29, 194, 221, 286
plain text 124, 189
platform 106, 286
plug-in 286
PNG compression 74, 158, 286
polynomial 71
Pony Express 142
popup blocker 194
port 176, 189
Portable Document Format (PDF) 116, 213, 286
PowerPC processor 117
powers of 10, table of 36
powers of 2 and 10, table of 36, 281
powers of 2, table of 36
Pride and Prejudice 17, 135, 158
printers, HP 183
Privacy Badger extension 206
privacy policy 218, 258
privacy, email 230
private browsing 219
processor family, x86 117
processor, AMD 52
ARM 52, 77, 117, 282
Intel 14, 51, 76, 117
PowerPC 117
program library 86, 123, 128, 140, 285
program testing 49, 65, 88, 128
program vs algorithm 75
programming language, Ada 9
assembly 76
BASIC 80
C 80–81, 83, 95, 116, 193
C# 96
C++ 80–81, 83, 95, 116
COBOL 79
F# 96
Fortran 79
Go 96
high-level 77
Java 81, 121, 193
JavaScript 82, 121, 193, 228, 285
Objective-C 81
Python 83, 122
Rust 96
Scratch 121
Swift 96, 121
Visual Basic 80
programming style 82
promiscuous mode 150
`prompt` function 124–125, 129
property, intellectual 89, 284
protocol 163, 166, 174, 286
protocol layers diagram 174
protocol, application-level 174
Bitcoin 181, 201, 261, 282
BitTorrent 181, 282
DHCP 166
HTTP 177, 187, 284
HTTPS 177, 189, 203, 206, 222, 255, 284
IMAP 180
IPv4 165
IPv6 165
SMTP 178, 180

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

proximity card 153
public records 225
public-key algorithm, RSA 254, 286
public-key cryptography 253
Punycode encoding 170
Python `for` loop 133
Python `import` 133
Python list 133
Python `matplotlib` 133
Python programming language 83, 122

QR code 161
quadratic algorithm 68–69, 286
quecto 209
Queen Elizabeth I 250
Queen Elizabeth II 188
query logs, AOL 226
quetta 209, 281
Quicksort algorithm 68, 91

radio-frequency identification (RFID) 152, 286
RAID file system 114
random access memory (RAM) 15, 43, 286
random vs sequential access 15
range, Ethernet 151
range, wireless 151
ransomware 61, 201, 286
RBG encoding 40
recipe as algorithm 63
recycle bin 112
Red Hat 96
Reddit 211, 227
registrar, domain name 167, 170, 286
reinforcement learning 240, 243, 286
repertoire, instruction 44, 51
representation, digital 32
Request for Comments (RFC) 167
reverse DNS lookup 168
reverse Turing test 56
RGB color representation 30, 40, 286
RIAA 181
right to repair 183
Ring, Amazon 246, 270
Ritchie, Dennis 80, 100
Rivest, Ronald 254, 256
RLHF 243
Roku 221
ronna 209, 281
ronto 209
root name server 169
`rot13` encryption algorithm 250
router *see* gateway
router vs gateway 164
router, wireless 169, 288
routing 166, 171
Rowe, Mike 170
RSA breach 205
RSA factoring challenge 254
RSA public-key algorithm 254, 286
Rust programming language 96

Safari browser 116, 123, 188, 204
safe harbor, DMCA 182
scareware 201
Schneier, Bruce 6, 207, 270
Scratch programming language 121
script kiddy 196
`script` tag 123, 129, 219
SD card file system 113
search algorithm, binary 66, 282
search engine diagram 212
search engine, AltaVista 212
 Bing 74, 189
 DuckDuckGo 215
 Google 74
secondary storage 16
secrecy, forward 256
secret-key cryptography 252
Section 230 145
Secure Digital (SD) card 19
SecurID breach 205
security by obscurity 252
security laws, Microsoft 194
selection sort algorithm 67
self-driving car 4, 60, 233, 239, 247
semantic error 79
semantics 122
sentiment analysis 240
sequential vs random access 15
SHA-1, SHA-2, SHA-3 message digest algorithm 256, 286
SHA-256 257
Shamir, Adi 254
Shannon, Claude 27
Shockley, William 20
shogi (game) 240
SI International System of Units 209, 281
SI units, table of 281
Signal 204
Silicon Valley 21
Silicon Valley TV series 160
Silk Road 263
SIM (Subscriber Identity Module) 154, 201
SIM-swapping attack 201
Simon, Herbert A. 233
simulator, Toy computer 45, 49, 129
Siri 233
slide rule 7
smart quotes 123
smartphone 216, 287
SMTP protocol 178, 180
Snapchat 258
sniffing 150, 203
Snowden, Edward xii, 3, 204, 224, 259–260
social engineering attack 197, 199, 287
social graph 224
software components 85
Software Development Kit (SDK) 86, 93, 286
software layers 174
solid state drive (SSD) 16, 110, 112, 287
sort times, table of 70
sound wave diagram 31
source code 95, 194, 283, 287
spam 197
spear phishing attack 199, 286
spectrum allocation 152, 162
spectrum auction 152
speech recognition 233
speed of light 157
`speedtest.net` 149
Spotify 17, 30, 160, 181
spyware 200, 287
SQL injection attack 202
SSD, wear leveling of 110, 112
SSH (Secure Shell) 178
Stallman, Richard 95
standard, 802.11 wireless 152, 157, 162, 282
 AES encryption 252, 282
 ASCII 34, 40, 57, 95, 158, 178, 282
 DES encryption 252, 283
 Unicode 34, 39, 57, 95, 287
standards 94, 143, 287
statement, assignment 125–126
statement, `if-else` 127
stingray 155, 287
Stonehenge 7
stored-program computer 15, 55
streaming 54
Street View, Google 239
Stroustrup, Bjarne 80
Stuxnet worm 61, 196
subroutine 85
subscription model 93, 228
Sun Microsystems 81, 94, 193
Sun vs Microsoft 193
supercomputer 54
supervised learning 236, 287
supply-chain attack 61
surveillance capitalism 3, 249
surveillance, Flock 270
swapping 101
Sweeney, Latanya 226
Swift programming language 96, 121
syntax 122
syntax error 78
system call 106, 287
system, embedded 59, 81

table of ASCII characters 34
table of ASCII with parity 161
table of powers of 10 36
table of powers of 2 36
table of powers of 2 and 10 36, 281
table of SI units 281
table of sort times 70
table, binary addition 39
table, binary multiplication 39
tablet 11, 18
tag manager, Google 219
tag, `form` 191
 HTML 189
 `img` 190
 `script` 123, 129, 219
TAILS operating system 261
Taiwan Semiconductor Manufacturing Company (TSMC) 23
Takeout, Google 206
Tanenbaum, Andrew 94
Task Manager, Windows 101
tax form as algorithm 63
taxi dataset, New York City 226
TCP acknowledgment 176
TCP port 176, 189
TCP segment diagram 176
TCP/IP 166, 174, 181
TCP/IP connection diagram 177
telegraph (Encyclopedia Britannica) 141
television, digital 162
Teller, Edward 35
Telnet 178, 184
`telnet` command 178
tera 17, 281
Tesla Autopilot 60, 93
testing, program 49, 65, 88, 128
tethering 157
text concatenation 125, 127
TextEdit 124
third-party cookie 197, 206
Thompson, Ken 100
TikTok xii, 145, 211, 227
Time Machine, Apple 206
time to live (TTL) 175
Tokyo in Unicode 39–40
top-level domain 167
`top500.org` 54
Tor browser 207, 259
Tor Project 259

For general queries, contact info@press.princeton.edu

© Copyright, Princeton University Press. No part of this book may be distributed, posted, or reproduced in any form by digital or mechanical means without prior written permission of the publisher.

Torvalds, Linus 103
Toy computer 44, 76
Toy computer simulator 45, 49, 129
Toy program in memory diagram 49
Toyota 217
`traceroute` command 172
tracking 216
tracking cookies 192, 217
tracking, JavaScript 219
trade secret 89
trademark 89
tradeoff 51, 83, 154, 160, 228, 268
training set 236
transformer architecture 243, 287
transistor 10, 20, 91
Transmission Control Protocol (TCP) 174, 287
transparency report, Amazon 230
  Facebook 230
  Google 230
TransUnion breach 202
trash folder 112
Traveling Salesman Problem 71
Trojan horse 196, 287
troll 287
troll, patent 91
Trump, Donald xii, xiv, 263
Tukey, John 27, 35
Turing Award 56, 68, 72, 76, 79, 100, 151, 177, 188, 235, 239, 254
Turing machine 55–56, 287
Turing test 55, 241
Turing test, reverse 56
Turing, Alan 55, 251
Tuvalu, `.tv` 167
two-factor authentication 205
typo-squatting 199, 287

uBlock Origin extension 206, 231
Ukraine cyber attack 61
Unicode domain name 168
Unicode standard 34, 39, 57, 95, 287
Unicode, Tokyo in 39–40
unifers.ai 221
United Healthcare 61
UnitedHealthcare breach 61, 202
units, table of SI 281
UNIVAC 80
universal computer 48
Universal Serial Bus (USB) 18, 287
universal Turing machine 55
Unix operating system 100–101, 103, 115, 117, 287
unsupervised learning 237, 287
URL 187, 189, 287
URL encoding 189
USB file system 113
USB virus 196
User Datagram Protocol (UDP) 174
UTF-8 encoding 58, 287

vacuum tube 10, 20
van Rossum, Guido 83
variable declaration 124, 126, 283, 287
VHS vs Betamax 94
vibe coding 245, 287
virtual currency 263
virtual machine 105, 116, 129, 136, 140, 193, 287
virtual machine license 105
virtual memory 101, 140, 287
virtual operating system 104
virtual operating system diagram 104
virtual operating system, Parallels 104
  VirtualBox 104
  VMware 104
virtual private network (VPN) 203, 287
VirtualBox virtual operating system 104
virus vs worm 195, 287
virus, Anna Kournikova 195–196
  floppy disk 196
  USB 196
  Visual Basic 195–196
Visual Basic interpreter 196
Visual Basic programming language 80
Visual Basic virus 195–196
VMware virtual operating system 104
voice over IP (VoIP) 145, 174, 287
von Neumann architecture 13, 24
von Neumann, John 11, 13, 41, 43–44, 51, 53
voting machines, computers in 61
voting, Internet 61
VPN breach 204

W3Schools 122
wafer, integrated circuit 21
walled garden 269, 272, 287
Waymo 60
Waze 153
wear leveling of SSD 110, 112
web beacon 194, 217, 288
web server, Apache 96
web server, NGINX 96
well known port 176
WhatsApp 204, 223, 271
`while` loop 126
`whois` command 168
Whorf, Benjamin 84
Wi-Fi 108, 152, 162, 288
Wikipedia 96
Wilkes, Maurice 75–76
Williamson, Malcolm 254
Windows File Recovery program 112
Windows operating system 11, 40, 100, 103, 105, 107, 117, 195–196, 198, 228
Windows Task Manager 101
wine measures, English 41
Wintel 117
wireless base station 151, 282
wireless encryption (WEP, WPA) 162
wireless range 151
wireless router 169, 288
wireless standard, 802.11 152, 157, 162, 282
Wireshark 150
World Wide Web Consortium (W3C) 188
worm vs virus 195, 288
worm, Morris 195
worm, Stuxnet 61, 196

x86 processor family 117
Xbox SDK 86
XCode IDE 86
Xerox PARC 149

Yahoo 175, 230, 260
Yamamoto, Isoroku 250
yopmail.com 207
yotta 209, 281
YouTube 211, 224, 227

zero-day attack 88
zetta 209, 211, 281
Zillow 225, 237
ZIP compression 74, 158
zombie 200
Zoom 144, 204
Zuboff, Shoshana 3, 249
Zuckerberg, Mark 184

For general queries, contact info@press.princeton.edu