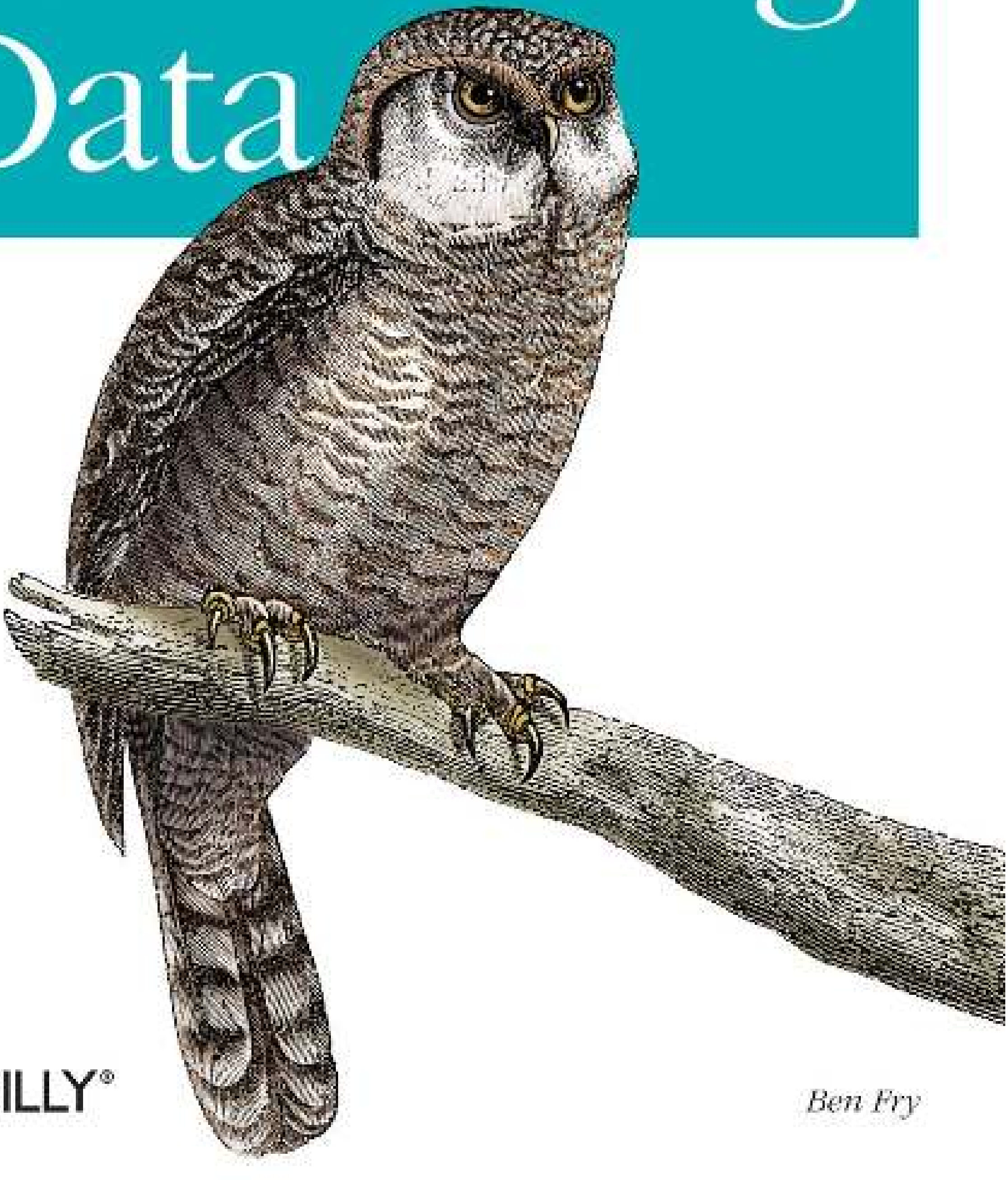
Exploring and Explaining Data with the Processing Environment

Visualizing Data



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Visualizing Data
by Ben Fry

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Table of Contents

Preface

When I show visualization projects to an audience, one of the most common questions is, "How do you do this?" Other books about data visualization do exist, but the most prominent ones are often collections of academic papers; in any case, few explain how to actually *build* representations. Books from the field of design that offer advice for creating visualizations see the field only in terms of static displays, ignoring the possibility of dynamic, software-based visualizations. A number spend most of their time dissecting what's wrong with given representations—sometimes providing solutions, but more often not.

In this book, I wanted to offer something for people who want to get started building their own visualizations, something to use as a jumping-off point for more complicated work. I don't cover everything, but I've tried to provide enough background so that you'll know where to go next.

I wrote this book because I wanted to have a way to make the ideas from *Computational Information Design*, my Ph.D. dissertation, more accessible to a wider audience. More specifically, I wanted to see these ideas actually applied, rather than limited to an academic document on a shelf. My dissertation covered the process of getting from data to understanding; in other words, from considering a pile of information to presenting it usefully, in a way that can be easily understood and interacted with. This process is covered in Chapter 1, and used throughout the book as a framework for working through visualizations.

Most of the examples in this book are written from scratch. Rather than relying on toolkits or libraries that produce charts or graphs, instead you learn how to create them using a little math, some lines and rectangles, and bits of text. Many readers may have tried some toolkits and found them lacking, particularly because they want to customize the display of their information. A tool that has generic uses will produce only generic displays, which can be disappointing if the displays do not suit your data set. Data can take many interesting forms that require unique types of display and interaction; this book aims to open up your imagination in ways that collections of bar and pie charts cannot.

This book uses Processing (*http://processing.org*), a simple programming environment and API that I co-developed with Casey Reas of UCLA. Processing's programming environment makes it easy to sit down and "sketch" code to produce visual images quickly. Once you outgrow the environment, it's possible to use a regular Java IDE to write Processing code because the API is based on Java. Processing is free to download and open source. It has been in development since 2001, and we've had about 100,000 people try it out in the last 12 months. Today Processing is used by tens of thousands of people for all manners of work. When I began writing this book, I debated which language and API to use. It could have been based on Java, but I realized I would have found myself re-implementing the Processing API to make things simple. It could have been based on Actionscript and Flash, but Flash is expensive to buy and tends to break down when dealing with larger data sets. Other scripting languages such as Python and Ruby are useful, but their execution speeds don't keep up with Java. In the end, Processing was the right combination of cost, ease of use, and execution speed.

The Audience for This Book

In the spring of 2007, I co-taught an Information Visualization course at Carnegie Mellon. Our 30 students ranged from a freshman in the art school to a Ph.D. candidate in computer science. In between were graduate students from the School of Design and various other undergrads. Their skill levels were enormously varied, but that was less important than their level of curiosity, and students who were curious and willing to put in some work managed to overcome the technical difficulties (for the art and design students) or the visual demands (for those with an engineering background).

This book is targeted at a similar range of backgrounds, if less academic. I'm trying to address people who want to ask questions, play with data, and gain an understanding of how to communicate information to others. For instance, the book is for web designers who want to build more complex visualizations than their tools will allow. It's also for software engineers who want to become adept at writing software that represents data—that calls on them to try out new skills, even if they have some background in building UIs. None of this is rocket science, but it isn't always obvious how to get started.

Fundamentally, this book is for people who have a data set, a curiosity to explore it, and an idea of what they want to communicate about it. The set of people who visualize data is growing extremely quickly as we deal with more and more information. Even more important, the audience has moved far beyond those who are experts in visualization. By making these ideas accessible to a wide range of people, we should see some truly amazing things in the next decade.

Background Information

Because the audience for this book includes both programmers and non-programmers, the material varies in complexity. Beginners should be able to pick it up and get through the first few chapters, but they may find themselves lost as we get into more complicated programming topics. If you're looking for a gentler introduction to programming with Processing, other books are available (including one written by Casey Reas and me) that are more suited to learning the concepts from scratch, though they don't cover the specifics of visualizing data. Chapters 1–4 can be understood by someone without any programming background, but the later chapters quickly become more difficult.

You'll be most successful with this book if you have some familiarity with writing code—whether it's Java, C++, or Actionscript. This is not an advanced text by any means, but a little background in writing code will go a long way toward understanding the concepts.

Overview of the Book

Chapter 1, *The Seven Stages of Visualizing Data*, covers the process for developing a useful visualization, from acquiring data to interacting with it. This is the framework we'll use as we attack problems in later chapters.

Chapter 2, *Getting Started with Processing*, is a basic introduction to the Processing environment and syntax. It provides a bit of background on the structure of the API and the philosophy behind the project's development.

Chapters 3 through 8 cover example projects that get progressively more complicated.

Chapter 3, *Mapping*, plots data points on a map, our first introduction to reading data from the disk and representing it on the screen.

Chapter 4, *Time Series*, covers several methods of plotting charts that represent how data changes over time.

Chapter 5, *Connections and Correlations*, is the first chapter that really delves into how we acquire and parse a data set. The example in this chapter reads data from the MLB.com web site and produces an image correlating player salaries and team performance over the course of a baseball season. It's an in-depth example illustrating how to scrape data from a web site that lacks an official API. These techniques can be applied to many other projects, even if you're not interested in baseball.

Chapter 6, *Scatterplot Maps*, answers the question, "How do zip codes relate to geography?" by developing a project that allows users to progressively refine a U.S. map as they type a zip code.

Chapter 7, *Trees, Hierarchies, and Recursion*, discusses trees and hierarchies. It covers recursion, an important topic when dealing with tree structures, and treemaps, a useful representation for certain kinds of tree data.

Chapter 8, *Networks and Graphs*, is about networks of information, also called graphs. The first half discusses ways to produce a representation of connections between many nodes in a network, and the second half shows an example of doing the same with web site traffic data to see how a site is used over time. The latter project also covers how to integrate Processing with Eclipse, a Java IDE.

The last three chapters contain reference material, including more background and techniques for acquiring and parsing data.

Chapter 9, *Acquiring Data*, is a kind of cookbook that covers all sorts of practical techniques, from reading data from files, to spoofing a web browser, to storing data in databases.

Chapter 10, *Parsing Data*, is also written in cookbook-style, with examples that illustrate the detective work involved in parsing data. Examples include parsing HTML tables, XML, compressed data, and SVG shapes. It even includes a basic example of watching a network connection to understand how an undocumented data protocol works.

Chapter 11, *Integrating Processing with Java*, covers the specifics of how the Processing API integrates with Java. It's more of an appendix aimed at advanced Java programmers who want to use the API with their own projects.

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I'd first like to thank O'Reilly Media for taking on this book. I was initially put in touch with Steve Weiss, who met with me to discuss the book in the spring of 2006. Steve later put me in touch with the Cambridge office, where Mike Hendrickson became a champion for the book and worked to make sure that the contract happened. Tim O'Reilly's enthusiasm along the way helped seal it.

I owe a great deal to my editor, Andy Oram, and assistant editor, Isabel Kunkle. Without Andy's hard work and helpful suggestions, or Isabel's focus on our schedule, I might still be working on the outline for Chapter 4. Thanks also to those who reviewed the draft manuscript: Brian DeLacey, Aidan Delaney, and Harry Hochheiser.

This book is based on ideas first developed as part of my doctoral work at the MIT Media Laboratory. For that I owe my advisor of six years, John Maeda, and my committee members, David Altshuler and Chris Pullman. Chris also pushed to have the ideas published properly, which was a great encouragement.

I'd also like to thank Casey Reas, my friend, inspiration, and collaborator on Processing, who has ensured that the project continues several years after its inception.

The content of the examples has been influenced by many courses I've taught as workshops or in classrooms over the last few years—in particular, my visualization courses at Harvard University and Carnegie Mellon (co-taught with Golan Levin), and workshops at Anderson Ranch in Colorado and at Hangar in Barcelona. I owe a lot to these student guinea pigs who taught me how to best explain this work.

Finally, thanks to my family, and immeasurable thanks to Shannon Hunt for editing, input, and moral support. Hers will be a tough act to follow while I return in kind as she writes *her* book in the coming months.

Conventions Used in This Book

The following typographical conventions are used in this book:

Plain text
: Indicates menu titles, menu options, menu buttons, and keyboard accelerators (such as Alt and Ctrl).

Italic
: Indicates new terms, URLs, email addresses, filenames, file extensions, pathnames, directories, and Unix utilities.

`Constant width`
: Indicates commands, options, variables, functions, types, classes, methods, HTML and XML tags, the contents of files, and the output from commands.

`Constant width bold`
: Shows commands or other text that should be typed literally by the user.

`Constant width italic`
: Shows text that should be replaced with user-supplied values.

This icon signifies a tip, suggestion, or general note.

This icon indicates a warning or caution.

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CHAPTER 1

The Seven Stages of Visualizing Data

The greatest value of a picture is when it forces *us to notice what we never expected to see.*
—John Tukey

What do the paths that millions of visitors take through a web site look like? How do the 3.1 billion A, C, G, and T letters of the human genome compare to those of the chimp or the mouse? Out of a few hundred thousand files on your computer's hard disk, which ones are taking up the most space, and how often do you use them? By applying methods from the fields of computer science, statistics, data mining, graphic design, and visualization, we can begin to answer these questions in a meaningful way that also makes the answers accessible to others.

All of the previous questions involve a large quantity of data, which makes it extremely difficult to gain a "big picture" understanding of its meaning. The problem is further compounded by the data's continually changing nature, which can result from new information being added or older information continuously being refined. This deluge of data necessitates new software-based tools, and its complexity requires extra consideration. Whenever we analyze data, our goal is to highlight its features in order of their importance, reveal patterns, and simultaneously show features that exist across multiple dimensions.

This book shows you how to make use of data as a resource that you might otherwise never tap. You'll learn basic visualization principles, how to choose the right kind of display for your purposes, and how to provide interactive features that will bring users to your site over and over again. You'll also learn to program in Processing, a simple but powerful environment that lets you quickly carry out the techniques in this book. You'll find Processing a good basis for designing interfaces around large data sets, but even if you move to other visualization tools, the ways of thinking presented here will serve you as long as human beings continue to process information the same way they've always done.

Why Data Display Requires Planning

Each set of data has particular display needs, and the *purpose* for which you're using the data set has just as much of an effect on those needs as the data itself. There are dozens of quick tools for developing graphics in a cookie-cutter fashion in office programs, on the Web, and elsewhere, but complex data sets used for specialized applications require unique treatment. Throughout this book, we'll discuss how the characteristics of a data set help determine what kind of visualization you'll use.

Too Much Information

When you hear the term "information overload," you probably know exactly what it means because it's something you deal with daily. In Richard Saul Wurman's book *Information Anxiety* (Doubleday), he describes how the *New York Times* on an average Sunday contains more information than a Renaissance-era person had access to in his entire lifetime.

But this is an exciting time. For $300, you can purchase a commodity PC that has thousands of times more computing power than the first computers used to tabulate the U.S. Census. The capability of modern machines is astounding. Performing sophisticated data analysis no longer requires a research laboratory, just a cheap machine and some code. Complex data sets can be accessed, explored, and analyzed by the public in a way that simply was not possible in the past.

The past 10 years have also brought about significant changes in the graphic capabilities of average machines. Driven by the gaming industry, high-end 2D and 3D graphics hardware no longer requires dedicated machines from specific vendors, but can instead be purchased as a $100 add-on card and is standard equipment for any machine costing $700 or more. When not used for gaming, these cards can render extremely sophisticated models with thousands of shapes, and can do so quickly enough to provide smooth, interactive animation. And these prices will only decrease—within a few years' time, accelerated graphics will be standard equipment on the aforementioned commodity PC.

Data Collection

We're getting better and better at collecting data, but we lag in what we can do with it. Most of the examples in this book come from freely available data sources on the Internet. Lots of data is out there, but it's not being used to its greatest potential because it's not being visualized as well as it could be. (More about this can be found in Chapter 9, which covers places to find data and how to retrieve it.)

With all the data we've collected, we still don't have many satisfactory answers to the sort of questions that we started with. This is the greatest challenge of our information-rich era: how can these questions be answered quickly, if not instantaneously? We're getting so good at measuring and recording things, why haven't we kept up with the methods to understand and communicate this information?

Thinking About Data

We also do very little sophisticated thinking about information itself. When AOL released a data set containing the search queries of millions of users that had been "randomized" to protect the innocent, articles soon appeared about how people could be identified by—and embarrassed by—information regarding their search habits. Even though we can collect this kind of information, we often don't know quite what it means. Was this a major issue or did it simply embarrass a few AOL users? Similarly, when millions of records of personal data are lost or accessed illegally, what does that mean? With so few people addressing data, our understanding remains quite narrow, boiling down to things like, "My credit card number might be stolen" or "Do I care if anyone sees what I search?"

Data Never Stays the Same

We might be accustomed to thinking about data as fixed values to be analyzed, but data is a moving target. How do we build representations of data that adjust to new values every second, hour, or week? This is a necessity because most data comes from the real world, where there are no absolutes. The temperature changes, the train runs late, or a product launch causes the traffic pattern on a web site to change drastically.

What happens when things start moving? How do we interact with "live" data? How do we unravel data as it changes over time? We might use animation to play back the evolution of a data set, or interaction to control what time span we're looking at. How can we write code for these situations?

What Is the Question?

As machines have enormously increased the capacity with which we can create (through measurements and sampling) and store data, it becomes easier to disassociate the data from the original reason for collecting it. This leads to an all-too frequent situation: approaching visualization problems with the question, "How can we possibly understand so much data?"

As a contrast, think about subway maps, which are abstracted from the complex shape of the city and are focused on the rider's goal: to get from one place to the next. Limiting the detail of each shape, turn, and geographical formation reduces this complex data set to answering the rider's question: "How do I get from point A to point B?"

Harry Beck invented the format now commonly used for subway maps in the 1930s, when he redesigned the map of the London Underground. Inspired by the layout of circuit boards, the map simplified the complicated Tube system to a series of vertical, horizontal, and 45° diagonal lines. While attempting to preserve as much of the relative physical layout as possible, the map shows only the connections between stations, as that is the only information that riders use to decide their paths.

When beginning a visualization project, it's common to focus on all the data that has been collected so far. The amounts of information might be enormous—people like to brag about how many gigabytes of data they've collected and how difficult their visualization problem is. But great information visualization never starts from the standpoint of the data set; it starts with questions. Why was the data collected, what's interesting about it, and what stories can it tell?

The most important part of understanding data is identifying the question that you want to answer. Rather than thinking about the data that was collected, think about how it will be used and work backward to what was collected. You collect data because you want to know something about it. If you don't really know why you're collecting it, you're just hoarding it. It's easy to say things like, "I want to know what's in it," or "I want to know what it means." Sure, but what's meaningful?

The more specific you can make your question, the more specific and clear the visual result will be. When questions have a broad scope, as in "exploratory data analysis" tasks, the answers themselves will be broad and often geared toward those who are themselves versed in the data. John Tukey, who coined the term Exploratory Data Analysis, said "...pictures based on exploration of data should force their messages upon us."[*] Too many data problems are labeled "exploratory" because the data collected is overwhelming, even though the original purpose was to answer a specific question or achieve specific results.

One of the most important (and least technical) skills in understanding data is asking good questions. An appropriate question shares an interest you have in the data, tries to convey it to others, and is curiosity-oriented rather than math-oriented. Visualizing data is just like any other type of communication: success is defined by your audience's ability to pick up on, and be excited about, your insight.

Admittedly, you may have a rich set of data to which you want to provide flexible access by not defining your question too narrowly. Even then, your goal should be to highlight key findings. There is a tendency in the visualization field to borrow from the statistics field and separate problems into *exploratory* and *expository*, but for the purposes of this book, this distinction is not useful. The same methods and process are used for both.

In short, a proper visualization is a kind of narrative, providing a clear answer to a question without extraneous details. By focusing on the original intent of the question, you can eliminate such details because the question provides a benchmark for what is and is not necessary.

[*] Tukey, John Wilder. *Exploratory Data Analysis*. Reading, MA: Addison-Wesley, 1977.

A Combination of Many Disciplines

Given the complexity of data, using it to provide a meaningful solution requires insights from diverse fields: statistics, data mining, graphic design, and information visualization. However, each field has evolved in isolation from the others.

Thus, visual design—-the field of mapping data to a visual form—typically does not address how to handle thousands or tens of thousands of items of data. Data mining techniques have such capabilities, but they are disconnected from the means to interact with the data. Software-based information visualization adds building blocks for interacting with and representing various kinds of abstract data, but typically these methods undervalue the aesthetic principles of visual design rather than embrace their strength as a necessary aid to effective communication. Someone approaching a data representation problem (such as a scientist trying to visualize the results of a study involving a few thousand pieces of genetic data) often finds it difficult to choose a representation and wouldn't even know what tools to use or books to read to begin.

Process

We must reconcile these fields as parts of a single process. Graphic designers can learn the computer science necessary for visualization, and statisticians can communicate their data more effectively by understanding the visual design principles behind data representation. The methods themselves are not new, but their isolation within individual fields has prevented them from being used together. In this book, we use a process that bridges the individual disciplines, placing the focus and consideration on how data is understood rather than on the viewpoint and tools of each individual field.

The process of understanding data begins with a set of numbers and a question. The following steps form a path to the answer:

Acquire
: Obtain the data, whether from a file on a disk or a source over a network.

Parse
: Provide some structure for the data's meaning, and order it into categories.

Filter
: Remove all but the data of interest.

Mine
: Apply methods from statistics or data mining as a way to discern patterns or place the data in mathematical context.

Represent
: Choose a basic visual model, such as a bar graph, list, or tree.

Refine
: Improve the basic representation to make it clearer and more visually engaging.

Interact
: Add methods for manipulating the data or controlling what features are visible.

Of course, these steps can't be followed slavishly. You can expect that they'll be involved at one time or another in projects you develop, but sometimes it will be four of the seven, and at other times all of them.

Part of the problem with the individual approaches to dealing with data is that the separation of fields leads to different people each solving an isolated part of the problem. When this occurs, something is lost at each transition—like a "telephone game" in which each step of the process diminishes aspects of the initial question under consideration. The initial format of the data (determined by how it is acquired and parsed) will often drive how it is considered for filtering or mining. The statistical method used to glean useful information from the data might drive the initial presentation. In other words, the final representation reflects the results of the statistical method rather than a response to the initial question.

Similarly, a graphic designer brought in at the next stage will most often respond to specific problems with the representation provided by the previous steps, rather than focus on the initial question. The visualization step might add a compelling and interactive means to look at the data filtered from the earlier steps, but the display is inflexible because the earlier stages of the process are hidden. Furthermore, practitioners of each of the fields that commonly deal with data problems are often unclear about how to traverse the wider set of methods and arrive at an answer.

This book covers the whole path from data to understanding: the transformation of a jumble of raw numbers into something coherent and useful. The data under consideration might be numbers, lists, or relationships between multiple entities.

It should be kept in mind that the term *visualization* is often used to describe the art of conveying a physical relationship, such as the subway map mentioned near the start of this chapter. That's a different kind of analysis and skill from *information visualization*, where the data is primarily numeric or symbolic (e.g., A, C, G, and T—the letters of genetic code—and additional annotations about them). The primary focus of this book is information visualization: for instance, a series of numbers that describes temperatures in a weather forecast rather than the shape of the cloud cover contributing to them.

An Example

To illustrate the seven steps listed in the previous section, and how they contribute to effective information visualization, let's look at how the process can be applied to understanding a simple data set. In this case, we'll take the zip code numbering system that the U.S. Postal Service uses. The application is not particularly advanced, but it provides a skeleton for how the process works. (Chapter 6 contains a full implementation of the project.)

What Is the Question?

All data problems begin with a question and end with a narrative construct that provides a clear answer. The Zipdecode project (described further in Chapter 6) was developed out of a personal interest in the relationship of the zip code numbering system to geographic areas. Living in Boston, I knew that numbers starting with a zero denoted places on the East Coast. Having spent time in San Francisco, I knew the initial numbers for the West Coast were all nines. I grew up in Michigan, where all our codes were four-prefixed. But what sort of area does the second digit specify? Or the third?

The finished application was initially constructed in a few hours as a quick way to take what might be considered a boring data set (a long list of zip codes, towns, and their latitudes and longitudes) and create something engaging for a web audience that explained how the codes related to their geography.

Acquire

The acquisition step involves obtaining the data. Like many of the other steps, this can be either extremely complicated (i.e., trying to glean useful data from a large system) or very simple (reading a readily available text file).

A copy of the zip code listing can be found on the U.S. Census Bureau web site, as it is frequently used for geographic coding of statistical data. The listing is a freely available file with approximately 42,000 lines, one for each of the codes, a tiny portion of which is shown in Figure 1-1.

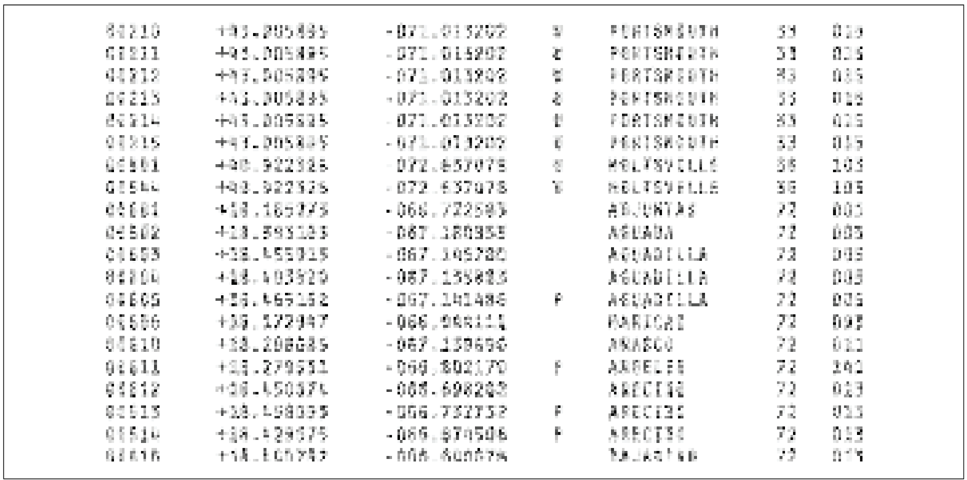

Figure 1-1. Zip codes in the format provided by the U.S. Census Bureau

Acquisition concerns how the user downloads your data as well as how you obtained the data in the first place. If the final project will be distributed over the Internet, as you design the application, you have to take into account the time required to download data into the browser. And because data downloaded to the browser is probably part of an even larger data set stored on the server, you may have to structure the data on the server to facilitate retrieval of common subsets.

Parse

After you acquire the data, it needs to be parsed—changed into a format that tags each part of the data with its intended use. Each line of the file must be broken along its individual parts; in this case, it must be delimited at each tab character. Then, each piece of data needs to be converted to a useful format. Figure 1-2 shows the layout of each line in the census listing, which we have to understand to parse it and get out of it what we want.

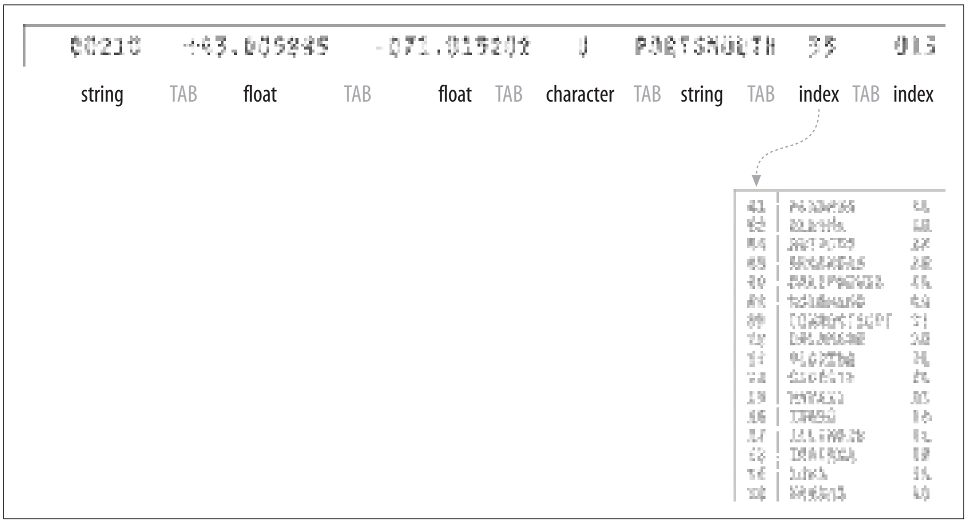

Figure 1-2. Structure of acquired data

Each field is formatted as a data type that we'll handle in a conversion program:

String
: A set of characters that forms a word or a sentence. Here, the city or town name is designated as a string. Because the zip codes themselves are not so much numbers as a series of digits (if they were numbers, the code 02139 would be stored as 2139, which is not the same thing), they also might be considered strings.

Float
: A number with decimal points (used for the latitudes and longitudes of each location). The name is short for *floating point*, from programming nomenclature that describes how the numbers are stored in the computer's memory.

Character

A single letter or other symbol. In this data set, a character sometimes designates special post offices.

Integer

A number without a fractional portion, and hence no decimal points (e.g., –14, 0, or 237).

Index

Data (commonly an integer or string) that maps to a location in another table of data. In this case, the index maps numbered codes to the names and two-digit abbreviations of states. This is common in databases, where such an index is used as a pointer into another table, sometimes as a way to compact the data further (e.g., a two-digit code requires less storage than the full name of the state or territory).

With the completion of this step, the data is successfully tagged and consequently more useful to a program that will manipulate or represent it in some way.

Filter

The next step involves filtering the data to remove portions not relevant to our use. In this example, for the sake of keeping it simple, we'll be focusing on the contiguous 48 states, so the records for cities and towns that are not part of those states—Alaska, Hawaii, and territories such as Puerto Rico—are removed. Another project could require significant mathematical work to place the data into a mathematical *model* or normalize it (convert it to an acceptable range of numbers).

Mine

This step involves math, statistics, and data mining. The data in this case receives only a simple treatment: the program must figure out the minimum and maximum values for latitude and longitude by running through the data (as shown in Figure 1-3) so that it can be presented on a screen at a proper scale. Most of the time, this step will be far more complicated than a pair of simple math operations.

Represent

This step determines the basic form that a set of data will take. Some data sets are shown as lists, others are structured like trees, and so forth. In this case, each zip code has a latitude and longitude, so the codes can be mapped as a two-dimensional plot, with the minimum and maximum values for the latitude and longitude used for the start and end of the scale in each dimension. This is illustrated in Figure 1-4.

The Represent stage is a linchpin that informs the single most important decision in a visualization project and can make you rethink earlier stages. How you choose to represent the data can influence the very first step (what data you acquire) and the third step (what particular pieces you extract).

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