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Tamara Munzner
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Preface

Why a New Book?

I wrote this book to scratch my own itch: the book I wanted to teach out of for my graduate visualization (vis) course did not exist. The itch grew through the years of teaching my own course at the University of British Columbia eight times, co-teaching a course at Stanford in 2001, and helping with the design of an early vis course at Stanford in 1996 as a teaching assistant.

I was dissatisfied with teaching primarily from original research papers. While it is very useful for graduate students to learn to read papers, what was missing was a synthesis view and a framework to guide thinking. The principles and design choices that I intended a particular paper to illustrate were often only indirectly alluded to in the paper itself. Even after assigning many papers or book chapters as preparatory reading before each lecture, I was frustrated by the many major gaps in the ideas discussed. Moreover, the reading load was so heavy that it was impossible to fit in any design exercises along the way, so the students only gained direct experience as designers in a single monolithic final project.

I was also dissatisfied with the lecture structure of my own course because of a problem shared by nearly every other course in the field: an incoherent approach to crosscutting the subject matter. Courses that lurch from one set of crosscuts to another are intellectually unsatisfying in that they make vis seem like a grab-bag of assorted topics rather than a field with a unifying theoretical framework. There are several major ways to crosscut vis material. One is by the field from which we draw techniques: cognitive science for perception and color, human–computer interaction for user studies and user-centered design, computer graphics for rendering, and so on. Another is by the problem domain addressed: for example, biology, software engineering, computer networking, medicine, casual use, and so on. Yet another is by the families of techniques: focus+context, overview/detail, volume rendering, and statistical graphics. Finally, evaluation is an important and central topic that should be interwoven throughout, but it did not fit into the standard pipelines and models. It was typically relegated to a single lecture, usually near the end, so that it felt like an afterthought.

Existing Books

Vis is a young field, and there are not many books that provide a synthesis view of the field. I saw a need for a next step on this front.

Tufte is a curator of glorious examples [Tufte 83, Tufte 91, Tufte 97], but he focuses on what can be done on the static printed page for purposes of exposition. The hallmarks of the last 20 years of computer-based vis are interactivity rather than simply static presentation and the use of vis for exploration of the unknown in addition to exposition of the known. Tufte's books do not address these topics, so while I use them as supplementary material, I find they cannot serve as the backbone for my own vis course. However, any or all of them would work well as supplementary reading for a course structured around this book; my own favorite for this role is *Envisioning Information* [Tufte 91].

Some instructors use *Readings in Information Visualization* [Card et al. 99]. The first chapter provides a useful synthesis view of the field, but it is only one chapter. The rest of the book is a collection of seminal papers, and thus it shares the same problem as directly reading original papers. Here I provide a book-length synthesis, and one that is informed by the wealth of progress in our field in the past 15 years.

Ware's book *Information Visualization: Perception for Design* [Ware 13] is a thorough book on vis design as seen through the lens of perception, and I have used it as the backbone for my own course for many years. While it discusses many issues on how one could design a vis, it does not cover what has been done in this field for the past 14 years from a synthesis point of view. I wanted a book that allows a beginning student to learn from this collective experience rather than starting from scratch. This book does not attempt to teach the very useful topic of perception per se; it covers only the aspects directly needed to get started with vis and leaves the rest as further reading. Ware's shorter book, *Visual Thinking for Design* [Ware 08], would be excellent supplemental reading for a course structured around this book.

This book offers a considerably more extensive model and framework than Spence's *Information Visualization* [Spence 07]. Wilkinson's *The Grammar of Graphics* [Wilkinson 05] is a deep and thoughtful work, but it is dense enough that it is more suitable for vis insiders than for beginners. Conversely, Few's *Show Me The Numbers* [Few 12] is extremely approachable and has been used at the undergraduate level, but the scope is much more limited than the coverage of this book.

The recent book *Interactive Data Visualization* [Ward et al. 10] works from the bottom up with algorithms as the base, whereas I work from the top down and stop one level above algorithmic considerations; our approaches are complementary. Like this book, it covers both nonspatial and spatial data. Similarly, the *Data Visualization* [Telea 07] book focuses on the algorithm level. The book on *The Visualization Toolkit* [Schroeder et al. 06] has a scope far beyond the vtk software, with considerable synthesis coverage of the concerns of visualizing spatial data. It has been used in many scientific visualization courses, but it does not cover nonspatial data. The voluminous *Visualization Handbook* [Hansen and Johnson 05] is an edited collection that contains a mix of synthesis material and research specifics; I refer to some specific chapters as good resources in my Further Reading sections at the end of each chapter in this book.

Audience

The primary audience of this book is students in a first vis course, particularly at the graduate level but also at the advanced undergraduate level. While admittedly written from a computer scientist's point of view, the book aims to be accessible to a broad audience including students in geography, library science, and design. It does not assume any experience with programming, mathematics, human–computer interaction, cartography, or graphic design; for those who do have such a background, some of the terms that I define in this book are connected with the specialized vocabulary from these areas through notes in the margins. Other audiences are people from other fields with an interest in vis, who would like to understand the principles and design choices of this field, and practitioners in the field who might use it as a reference for a more formal analysis and improvements of production vis applications.

I wrote this book for people with an interest in the design and analysis of vis idioms and systems. That is, this book is aimed at vis designers, both nascent and experienced. This book is not directly aimed at vis end users, although they may well find some of this material informative.

The book is aimed at both those who take a problem-driven approach and those who take a technique-driven approach. Its focus is on broad synthesis of the general underpinnings of vis in terms of principles and design choices to provide a framework for the design and analysis of techniques, rather than the algorithms to instantiate those techniques.

The book features a unified approach encompassing information visualization techniques for abstract data, scientific visualization techniques for spatial data, and visual analytics techniques for interleaving data transformation and analysis with interactive visual exploration.

Who's Who

I use pronouns in a deliberate way in this book, to indicate roles. **I** am the author of this book. I cover many ideas that have a long and rich history in the field, but I also advocate opinions that are not necessarily shared by all visualization researchers and practitioners. The pronoun **you** means the reader of this book; I address you as if you're designing or analyzing a visualization system. The pronoun **they** refers to the intended users, the target audience for whom a visualization system is designed. The pronoun **we** refers to all humans, especially in terms of our shared perceptual and cognitive responses.

I'll also use the abbreviation **vis** throughout this book, since *visualization* is quite a mouthful!

Structure: What's in This Book

The book begins with a definition of vis and walks through its many implications in Chapter 1, which ends with a high-level introduction to an analysis framework of breaking down vis design according *what–why–how* questions that have *data–task–idiom* answers. Chapter 2 addresses the *what* question with answers about data abstractions, and Chapter 3 addresses the *why* question with task abstractions, including an extensive discussion of deriving new data, a preview of the framework of design choices for *how* idioms can be designed, and several examples of analysis through this framework.

Chapter 4 extends the analysis framework to two additional levels: the domain situation level on top and the algorithm level on the bottom, with the what/why level of data and task abstraction and the how level of visual encoding and interaction idiom design in between the two. This chapter encourages using methods to validate your design in a way that matches up with these four levels.

Chapter 5 covers the principles of marks and channels for encoding information. Chapter 6 presents eight rules of thumb for design.

The core of the book is the framework for analyzing how vis idioms can be constructed out of design choices. Three chapters cover choices of how to visually encode data by arranging space: Chapter 7 for tables, Chapter 8 for spatial data, and Chapter 9 for networks. Chapter 10 continues with the choices for mapping color and other channels in visual encoding. Chapter 11 discusses ways to manipulate and change a view. Chapter 12 covers ways to facet data between multiple views. Choices for how to reduce the amount of data shown in each view are covered in Chapter 13, and Chapter 14 covers embedding information about a focus set within the context of overview data. Chapter 15 wraps up the book with six case studies that are analyzed in detail with the full framework.

Each design choice is illustrated with concrete examples of specific idioms that use it. Each example is analyzed by decomposing its design with respect to the design choices that have been presented so far, so these analyses become more extensive as the chapters progress; each ends with a table summarizing the analysis. The book's intent is to get you familiar with analyzing existing idioms as a springboard for designing new ones.

I chose the particular set of concrete examples in this book as evocative illustrations of the space of vis idioms and my way to approach vis analysis. Although this set of examples does cover many of the more popular idioms, it is certainly not intended to be a complete enumeration of all useful idioms; there are many more that have been proposed that aren't in here. These examples also aren't intended to be a historical record of who first proposed which ideas: I often pick more recent examples rather than the very first use of a particular idiom.

All of the chapters start with a short section called **The Big Picture** that summarizes their contents, to help you quickly determine whether a chapter covers material that you care about. They all end with a **Further Reading** section that points you to more information about their topics. Throughout the book are boxes in the margins: vocabulary notes in purple starting with a star, and cross-reference notes in blue starting with a triangle. Terms are highlighted in purple where they are defined for the first time.

The book has an accompanying web page at http://www.cs.ubc.ca/~tmm/vadbook with errata, pointers to courses that use the book in different ways, example lecture slides covering the material, and downloadable versions of the diagram figures.

What's Not in This Book

This book focuses on the abstraction and idiom levels of design and doesn't cover the domain situation level or the algorithm levels.

I have left out algorithms for reasons of space and time, not of interest. The book would need to be much longer if it covered algorithms at any reasonable depth; the middle two levels provide more than enough material for a single volume of readable size. Also, many good resources already exist to learn about algorithms, including original papers and some of the previous books discussed above. Some points of entry for this level are covered in Further Reading sections at the end of each chapter. Moreover, this book is intended to be accessible to people without a computer science background, a decision that precludes algorithmic detail. A final consideration is that the state of the art in algorithms changes quickly; this book aims to provide a framework for thinking about design that will age more gracefully. The book includes many concrete examples of previous vis tools to illustrate points in the design space of possible idioms, not as the final answer for the very latest and greatest way to solve a particular design problem.

The domain situation level is not as well studied in the vis literature as the algorithm level, but there are many relevant resources from other literatures including human–computer interaction. Some points of entry for this level are also covered in Further Reading.

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Chapter 1

What's Vis, and Why Do It?

1.1 The Big Picture

This book is built around the following definition of visualization—**vis**, for short:

> Computer-based **visualization** systems provide visual representations of datasets designed to help people carry out tasks more effectively.
>
> Visualization is suitable when there is a need to augment human capabilities rather than replace people with computational decision-making methods. The design space of possible vis idioms is huge, and includes the considerations of both how to create and how to interact with visual representations. Vis design is full of trade-offs, and most possibilities in the design space are ineffective for a particular task, so validating the effectiveness of a design is both necessary and difficult. Vis designers must take into account three very different kinds of resource limitations: those of computers, of humans, and of displays. Vis usage can be analyzed in terms of why the user needs it, what data is shown, and how the idiom is designed.

I'll discuss the rationale behind many aspects of this definition as a way of getting you to think about the scope of this book, and about visualization itself:

- Why have a human in the decision-making loop?
- Why have a computer in the loop?
- Why use an external representation?
- Why depend on vision?

- Why show the data in detail?
- Why use interactivity?
- Why is the vis idiom design space huge?
- Why focus on tasks?
- Why are most designs ineffective?
- Why care about effectiveness?
- Why is validation difficult?
- Why are there resource limitations?
- Why analyze vis?

1.2 Why Have a Human in the Loop?

Vis allows people to analyze data when they don't know exactly what questions they need to ask in advance.

The modern era is characterized by the promise of better decision making through access to more data than ever before. When people have well-defined questions to ask about data, they can use purely computational techniques from fields such as statistics and machine learning.* Some jobs that were once done by humans can now be completely automated with a computer-based solution. If a fully automatic solution has been deemed to be acceptable, then there is no need for human judgement, and thus no need for you to design a vis tool. For example, consider the domain of stock market trading. Currently, there are many deployed systems for high-frequency trading that make decisions about buying and selling stocks when certain market conditions hold, when a specific price is reached, for example, with no need at all for a time-consuming check from a human in the loop. You would not want to design a vis tool to help a person make that check faster, because even an augmented human will not be able to reason about millions of stocks every second.

★ The field of **machine learning** is a branch of artificial intelligence where computers can handle a wide variety of new situations in response to data-driven training, rather than by being programmed with explicit instructions in advance.

However, many analysis problems are ill specified: people don't know how to approach the problem. There are many possible questions to ask—anywhere from dozens to thousands or more—and people don't know which of these many questions are the right ones in advance. In such cases, the best path forward is an analysis process with a human in the loop, where you can exploit the powerful pattern detection properties of the human visual system in your design. Vis systems are appropriate for use when your goal is to augment human capabilities, rather than completely replace the human in the loop.

You can design vis tools for many kinds of uses. You can make a tool intended for transitional use where the goal is to "work itself out of a job", by helping the designers of future solutions that are purely computational. You can also make a tool intended for long-term use, in a situation where there is no intention of replacing the human any time soon.

For example, you can create a vis tool that's a stepping stone to gaining a clearer understanding of analysis requirements before developing formal mathematical or computational models. This kind of tool would be used very early in the transition process in a highly exploratory way, before even starting to develop any kind of automatic solution. The outcome of designing vis tools targeted at specific real-world domain problems is often a much crisper understanding of the user's task, in addition to the tool itself.

In the middle stages of a transition, you can build a vis tool aimed at the designers of a purely computational solution, to help them refine, debug, or extend that system's algorithms or understand how the algorithms are affected by changes of parameters. In this case, your tool is aimed at a very different audience than the end users of that eventual system; if the end users need visualization at all, it might be with a very different interface. Returning to the stock market example, a higher-level system that determines which of multiple trading algorithms to use in varying circumstances might require careful tuning. A vis tool to help the algorithm developers analyze its performance might be useful to these developers, but not to people who eventually buy the software.

You can also design a vis tool for end users in conjunction with other computational decision making to illuminate whether the automatic system is doing the right thing according to human judgement. The tool might be intended for interim use when making deployment decisions in the late stages of a transition, for example, to see if the result of a machine learning system seems to be trustworthy before entrusting it to spend millions of dollars trading stocks. In some cases vis tools are abandoned after that decision is made; in other cases vis tools continue to be in play with long-term use to monitor a system, so that people can take action if they spot unreasonable behavior.

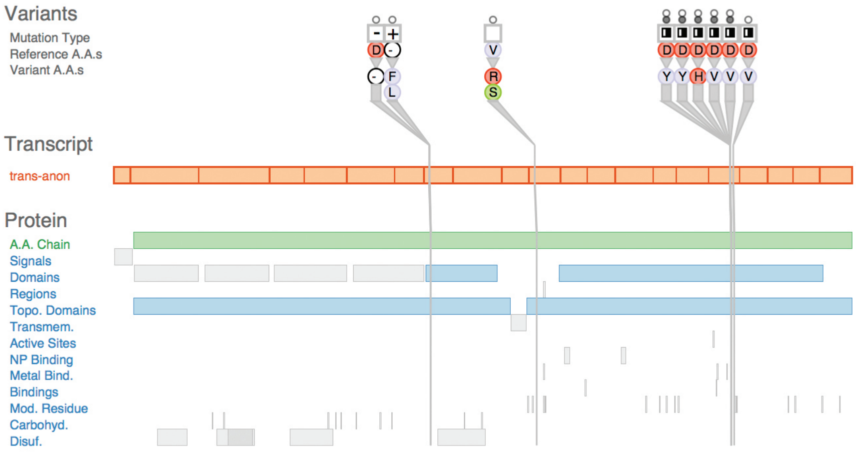


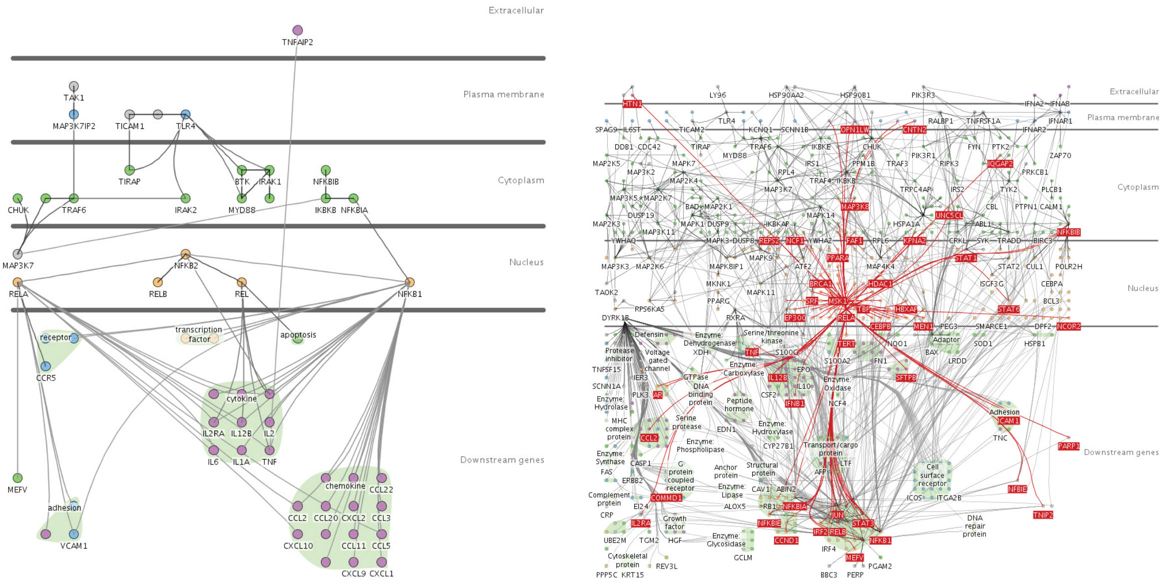
Figure 1.1. The Variant View vis tool supports biologists in assessing the impact of genetic variants by speeding up the exploratory analysis process. From [Ferstay et al. 13, Figure 1].

In contrast to these transitional uses, you can also design vis tools for long-term use, where a person will stay in the loop indefinitely. A common case is exploratory analysis for scientific discovery, where the goal is to speed up and improve a user's ability to generate and check hypotheses. Figure 1.1 shows a vis tool designed to help biologists studying the genetic basis of disease through analyzing DNA sequence variation. Although these scientists make heavy use of computation as part of their larger workflow, there's no hope of completely automating the process of cancer research any time soon.

You can also design vis tools for presentation. In this case, you're supporting people who want to explain something that they already know to others, rather than to explore and analyze the unknown. For example, *The New York Times* has deployed sophisticated interactive visualizations in conjunction with news stories.

1.3 Why Have a Computer in the Loop?

By enlisting computation, you can build tools that allow people to explore or present large datasets that would be completely infeasible to draw by hand, thus opening up the possibility of seeing how datasets change over time.



(a) (b)

Figure 1.2. The Cerebral vis tool captures the style of hand-drawn diagrams in biology textbooks with vertical layers that correspond to places within a cell where interactions between genes occur. (a) A small network of 57 nodes and 74 edges might be possible to lay out by hand with enough patience. (b) Automatic layout handles this large network of 760 nodes and 1269 edges and provides a substrate for interactive exploration: the user has moved the mouse over the MSK1 gene, so all of its immmediate neighbors in the network are highlighted in red. From [Barsky et al. 07, Figures 1 and 2].

People could create visual representations of datasets manually, either completely by hand with pencil and paper, or with computerized drawing tools where they individually arrange and color each item. The scope of what people are willing and able to do manually is strongly limited by their attention span; they are unlikely to move beyond tiny static datasets. Arranging even small datasets of hundreds of items might take hours or days. Most real-world datasets are much larger, ranging from thousands to millions to even more. Moreover, many datasets change dynamically over time. Having a computer-based tool generate the visual representation automatically obviously saves human effort compared to manual creation.

As a designer, you can think about what aspects of hand-drawn diagrams are important in order to automatically create drawings that retain the hand-drawn spirit. For example, Figure 1.2 shows an example of a vis tool designed to show interactions between genes in a way similar to stylized drawings that appear in biology textbooks, with vertical layers that correspond to the location within the cell where the interaction occurs [Barsky et al. 07]. Figure 1.2(a) could be done by hand, while Figure 1.2(b) could not.

1.4 Why Use an External Representation?

External representations augment human capacity by allowing us to surpass the limitations of our own internal cognition and memory.

Vis allows people to offload internal cognition and memory usage to the perceptual system, using carefully designed images as a form of **external representations**, sometimes also called *external memory*. External representations can take many forms, including touchable physical objects like an abacus or a knotted string, but in this book I focus on what can be shown on the two-dimensional display surface of a computer screen.

Diagrams can be designed to support perceptual inferences, which are very easy for humans to make. The advantages of diagrams as external memory is that information can be organized by spatial location, offering the possibility of accelerating both search and recognition. Search can be sped up by grouping all the items needed for a specific problem-solving inference together at the same location. Recognition can also be facilitated by grouping all the relevant information about one item in the same location, avoiding the need for matching remembered symbolic labels. However, a nonoptimal diagram may group irrelevant information together, or support perceptual inferences that aren't useful for the intended problem-solving process.

1.5 Why Depend on Vision?

Visualization, as the name implies, is based on exploiting the human visual system as a means of communication. I focus exclusively on the visual system rather than other sensory modalities because it is both well characterized and suitable for transmitting information.

The visual system provides a very high-bandwidth channel to our brains. A significant amount of visual information processing occurs in parallel at the preconscious level. One example is visual popout, such as when one red item is immediately noticed from a sea of gray ones. The popout occurs whether the field of other objects is large or small because of processing done in parallel across the entire field of vision. Of course, our visual systems also feed into higher-level processes that involve the conscious control of attention.

Sound is poorly suited for providing overviews of large information spaces compared with vision. An enormous amount of background visual information processing in our brains underlies our ability to think and act as if we see a huge amount of information at once, even though technically we see only a tiny part of our visual field in high resolution at any given instant. In contrast, we experience the perceptual channel of sound as a sequential stream, rather than as a simultaneous experience where what we hear over a long period of time is automatically merged together. This crucial difference may explain why *sonification* has never taken off despite many independent attempts at experimentation.

The other senses can be immediately ruled out as communication channels because of technological limitations. The perceptual channels of taste and smell don't yet have viable recording and reproduction technology at all. Haptic input and feedback devices exist to exploit the touch and kinesthetic perceptual channels, but they cover only a very limited part of the dynamic range of what we can sense. Exploration of their effectiveness for communicating abstract information is still at a very early stage.

► Chapter 5 covers implications of visual perception that are relevant for vis design.

1.6 Why Show the Data in Detail?

Vis tools help people in situations where seeing the dataset structure in detail is better than seeing only a brief summary of it. One of these situations occurs when exploring the data to find patterns, both to confirm expected ones and find unexpected ones. Another occurs when assessing the validity of a statistical model, to judge whether the model in fact fits the data.

Statistical characterization of datasets is a very powerful approach, but it has the intrinsic limitation of losing information through summarization. Figure 1.3 shows Anscombe's Quartet, a suite of four small datasets designed by a statistician to illustrate how datasets that have identical descriptive statistics can have very different structures that are immediately obvious when the dataset is shown graphically [Anscombe 73]. All four have identical mean, variance, correlation, and linear regression lines. If you

Anscombe's Quartet: Raw Data

	1		2		3		4	
	X	Y	X	Y	X	Y	X	Y
	10.0	8.04	10.0	9.14	10.0	7.46	8.0	6.58
	8.0	6.95	8.0	8.14	8.0	6.77	8.0	5.76
	13.0	7.58	13.0	8.74	13.0	12.74	8.0	7.71
	9.0	8.81	9.0	8.77	9.0	7.11	8.0	8.84
	11.0	8.33	11.0	9.26	11.0	7.81	8.0	8.47
	14.0	9.96	14.0	8.10	14.0	8.84	8.0	7.04
	6.0	7.24	6.0	6.13	6.0	6.08	8.0	5.25
	4.0	4.26	4.0	3.10	4.0	5.39	19.0	12.50
	12.0	10.84	12.0	9.13	12.0	8.15	8.0	5.56
	7.0	4.82	7.0	7.26	7.0	6.42	8.0	7.91
	5.0	5.68	5.0	4.74	5.0	5.73	8.0	6.89
Mean	9.0	7.5	9.0	7.5	9.0	7.5	9.0	7.5
Variance	10.0	3.75	10.0	3.75	10.0	3.75	10.0	3.75
Correlation	0.816		0.816		0.816		0.816	

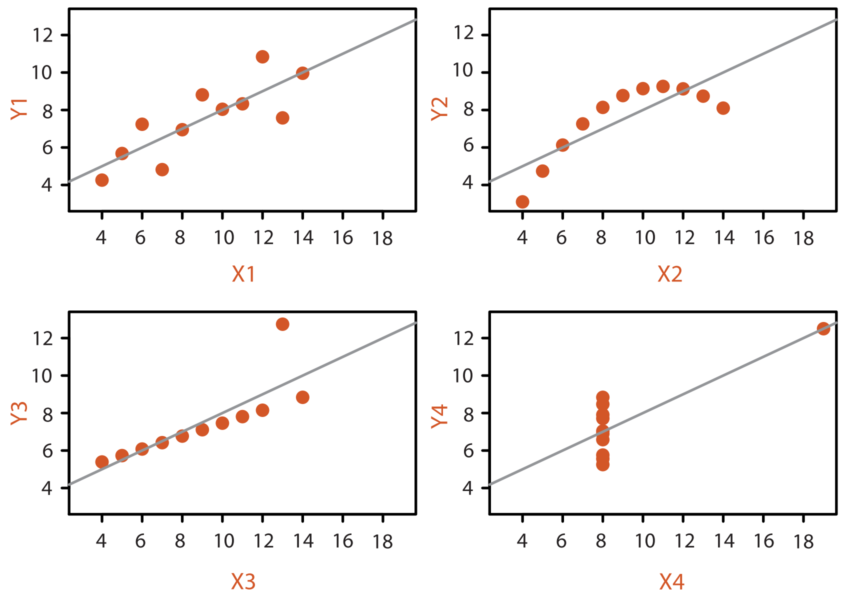


Figure 1.3. Anscombe's Quartet is four datasets with identical simple statistical properties: mean, variance, correlation, and linear regression line. However, visual inspection immediately shows how their structures are quite different. After [Anscombe 73, Figures 1–4].

are familiar with these statistical measures, then the scatterplot of the first dataset probably isn't surprising, and matches your intuition. The second scatterplot shows a clear nonlinear pattern in the data, showing that summarizing with linear regression doesn't adequately capture what's really happening. The third dataset shows how a single outlier can lead to a regression line that's misleading in a different way because its slope doesn't quite match the line that our eyes pick up clearly from the rest of the data. Finally, the fourth dataset shows a truly pernicious case where these measures dramatically mislead, with a regression line that's almost perpendicular to the true pattern we immediately see in the data.

The basic principle illustrated by Anscombe's Quartet, that a single summary is often an oversimplification that hides the true structure of the dataset, applies even more to large and complex datasets.

1.7 Why Use Interactivity?

Interactivity is crucial for building vis tools that handle complexity. When datasets are large enough, the limitations of both people and displays preclude just showing everything at once; **interaction** where user actions cause the view to change is the way forward. Moreover, a single static view can show only one aspect of a dataset. For some combinations of simple datasets and tasks, the user may only need to see a single visual encoding. In contrast, an interactively changing display supports many possible queries.

In all of these cases, interaction is crucial. For example, an interactive vis tool can support investigation at multiple levels of detail, ranging from a very high-level overview down through multiple levels of summarization to a fully detailed view of a small part of it. It can also present different ways of representing and summarizing the data in a way that supports understanding the connections between these alternatives.

Before the widespread deployment of fast computer graphics, visualization was limited to the use of static images on paper. With computer-based vis, interactivity becomes possible, vastly increasing the scope and capabilities of vis tools. Although static representations are indeed within the scope of this book, interaction is an intrinsic part of many idioms.

1.8 Why Is the Vis Idiom Design Space Huge?

A vis **idiom** is a distinct approach to creating and manipulating visual representations. There are many ways to create a **visual encoding** of data as a single picture. The design space of possibilities gets even bigger when you consider how to manipulate one or more of these pictures with **interaction**.

Many vis idioms have been proposed. Simple static idioms include many chart types that have deep historical roots, such as scatterplots, bar charts, and line charts. A more complicated idiom can link together multiple simple charts through interaction. For example, selecting one bar in a bar chart could also result in highlighting associated items in a scatterplot that shows a different view of the same data. Figure 1.4 shows an even more complex idiom that supports incremental layout of a multilevel network through interactive navigation. Data from Internet Movie Database showing all movies connected to Sharon Stone is shown, where actors are represented as grey square nodes and links between them

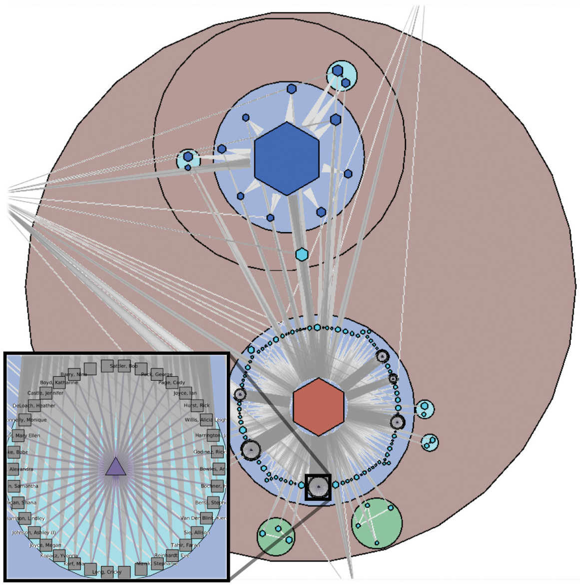


Figure 1.4. The Grouse vis tool features a complex idiom that combines visual encoding and interaction, supporting incremental layout of a network through interactive navigation. From [Archambault et al. 07a, Figure 5].

mean appearance in the same movie. The user has navigated by opening up several metanodes, shown as discs, to see structure at many levels of the hierarchy simultaneously; metanode color encodes the topological structure of the network features it contains, and hexagons indicate metanodes that are still closed. The inset shows the details of the opened-up clique of actors who all appear in the movie *Anything but Here*, with name labels turned on.

► Compound networks are discussed further in Section 9.5.

This book provides a framework for thinking about the space of vis design idioms systematically by considering a set of design choices, including how to encode information with spatial position, how to facet data between multiple views, and how to reduce the amount of data shown by filtering and aggregation.

1.9 Why Focus on Tasks?

A tool that serves well for one task can be poorly suited for another, for exactly the same dataset. The task of the users is an equally important constraint for a vis designer as the kind of data that the users have.

Reframing the users' task from domain-specific form into abstract form allows you to consider the similarities and differences between what people need across many real-world usage contexts. For example, a vis tool can support presentation, or discovery, or enjoyment of information; it can also support producing more information for subsequent use. For discovery, vis can be used to generate new hypotheses, as when exploring a completely unfamiliar dataset, or to confirm existing hypotheses about some dataset that is already partially understood.

► The space of task abstractions is discussed in detail in Chapter 3.

1.10 Why Focus on Effectiveness?

The focus on effectiveness is a corollary of defining vis to have the goal of supporting user tasks. This goal leads to concerns about correctness, accuracy, and truth playing a very central role in vis. The emphasis in vis is different from other fields that also involve making images: for example, art emphasizes conveying emotion, achieving beauty, or provoking thought; movies and comics emphasize telling a narrative story; advertising emphasizes setting a mood or selling. For the goals of emotional engagement, storytelling, or allurement, the deliberate distortion and even fabrication of facts is often entirely appropriate, and of course fiction is as respectable as nonfiction. In contrast, a vis designer does not typically have artistic license. Moreover, the phrase "it's not just about making pretty pictures" is a common and vehement assertion in vis, meaning that the goals of the designer are not met if the result is beautiful but not effective.

However, no picture can communicate the truth, the whole truth, and nothing but the truth. The correctness concerns of a vis designer are complicated by the fact that *any* depiction of data is an abstraction where choices are made about which aspects to emphasize. Cartographers have thousands of years of experience with articulating the difference between the abstraction of a map and the terrain that it represents. Even photographing a real-world scene involves choices of abstraction and emphasis; for example, the photographer chooses what to include in the frame.

► Abstraction is discussed in more detail in Chapters 3 and 4.

1.11 Why Are Most Designs Ineffective?

The most fundamental reason that vis design is a difficult enterprise is that the vast majority of the possibilities in the design space will be ineffective for any specific usage context. In some cases, a possible design is a poor match with the properties of the human perceptual and cognitive systems. In other cases, the design would be comprehensible by a human in some other setting, but it's a bad match with the intended task. Only a very small number of possibilities are in the set of reasonable choices, and of those only an even smaller fraction are excellent choices. Randomly choosing possibilities is a bad idea because the odds of finding a very good solution are very low.

Figure 1.5 contrasts two ways to think about design in terms of traversing a search space. In addressing design problems, it's not a very useful goal to **optimize**; that is, to find the very best choice. A more appropriate goal when you design is to **satisfy**; that is, to find one of the many possible good solutions rather than one of the even larger number of bad ones. The diagram shows five spaces, each of which is progressively smaller than the previous. First, there is the space of all possible solutions, including potential solutions that nobody has ever thought of before. Next, there is the set of possibilities that are *known* to you, the vis designer. Of course, this set might be small if you are a novice designer who is not aware of the full array of methods that have been proposed in the past. If you're in that situation, one of the goals of this book is to enlarge the set of methods that you know about. The next set is the

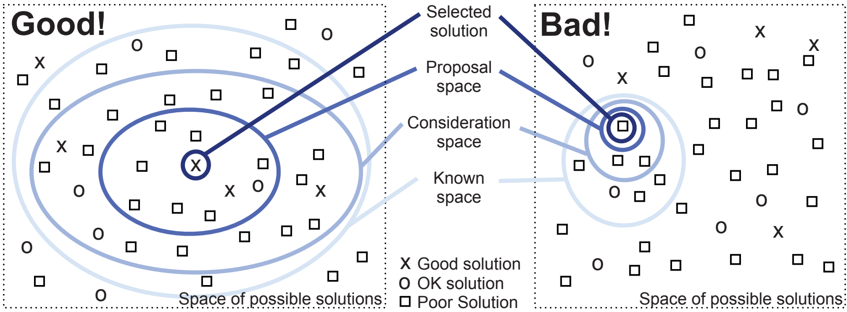


Figure 1.5. A search space metaphor for vis design.

consideration space, which contains the solutions that you actively consider. This set is necessarily smaller than the known space, because you can't consider what you don't know. An even smaller set is the *proposal* space of possibilities that you investigate in detail. Finally, one of these becomes the *selected* solution.

Figure 1.5 contrasts a good strategy on the left, where the known and consideration spaces are large, with a bad strategy on the right, where these spaces are small. The problem of a small consideration space is the higher probability of only considering ok or poor solutions and missing a good one. A fundamental principle of design is to consider multiple alternatives and then choose the best, rather than to immediately fixate on one solution without considering any alternatives. One way to ensure that more than one possibility is considered is to explicitly generate multiple ideas in parallel. This book is intended to help you, the designer, entertain a broad consideration space by systematically considering many alternatives and to help you rule out some parts of the space by noting when there are mismatches of possibilities with human capabilities or the intended task.

As with all design problems, vis design cannot be easily handled as a simple process of optimization because trade-offs abound. A design that does well by one measure will rate poorly on another. The characterization of trade-offs in the vis design space is a very open problem at the frontier of vis research. This book provides several guidelines and suggested processes, based on my synthesis of what is currently known, but it contains few absolute truths.

► Chapter 4 introduces a model for thinking about the design process at four different levels; the model is intended to guide your thinking through these trade-offs in a systematic way.

1.12 Why Is Validation Difficult?

The problem of **validation** for a vis design is difficult because there are so many questions that you could ask when considering whether a vis tool has met your design goals.

How do you know if it works? How do you argue that one design is better or worse than another for the intended users? For one thing, what does *better* mean? Do users get something done faster? Do they have more fun doing it? Can they work more effectively? What does *effectively* mean? How do you measure *insight* or *engagement*? What is the design better than? Is it better than another vis system? Is it better than doing the same things manually, without visual support? Is it better than doing the same things completely automatically? And what sort of thing does it do better? That is, how do you decide what sort of task the users should do when testing the system? And who is this *user*? An expert who has done this task for decades, or a novice who needs the task to be explained before they begin? Are they familiar with how the system works from using it for a long time, or are they seeing it for the first time? A concept like *faster* might seem straightforward, but tricky questions still remain. Are the users limited by the speed of their own thought process, or their ability to move the mouse, or simply the speed of the computer in drawing each picture?

How do you decide what sort of *benchmark* data you should use when testing the system? Can you characterize what classes of data the system is suitable for? How might you measure the *quality* of an image generated by a vis tool? How well do any of the automatically computed quantitative metrics of quality match up with human judgements? Even once you limit your considerations to purely computational issues, questions remain. Does the complexity of the algorithm depend on the number of data items to show or the number of pixels to draw? Is there a trade-off between computer speed and computer memory usage?

► Chapter 4 answers these questions by providing a framework that addresses when to use what methods for validating vis designs.

1.13 Why Are There Resource Limitations?

When designing or analyzing a vis system, you must consider at least three different kinds of limitations: computational capacity, human perceptual and cognitive capacity, and display capacity.

Vis systems are inevitably used for larger datasets than those they were designed for. Thus, **scalability** is a central concern: designing systems to handle large amounts of data gracefully. The continuing increase in dataset size is driven by many factors: improvements in data acquisition and sensor technology, bringing real-world data into a computational context; improvements in computer capacity, leading to ever-more generation of data from within computational environments including simulation and logging; and the increasing reach of computational infrastructure into every aspect of life.

As with any application of computer science, computer time and memory are limited resources, and there are often soft and hard constraints on the availability of these resources. For instance, if your vis system needs to interactively deliver a response to user input, then when drawing each frame you must use algorithms that can run in a fraction of a second rather than minutes or hours. In some scenarios, users are unwilling or unable to wait a long time for the system to preprocess the data before they can interact with it. A soft constraint is that the vis system should be parsimonious in its use of computer memory because the user needs to run other programs simultaneously. A hard constraint is that even if the vis system can use nearly all available memory in the computer, dataset size can easily outstrip that finite capacity. Designing systems that gracefully handle larger datasets that do not fit into core memory requires significantly more complex algorithms. Thus, the computational complexity of algorithms for dataset preprocessing, transformation, layout, and rendering is a major concern. However, computational issues are by no means the only concern!

On the human side, memory and attention are finite resources. Chapter 5 will discuss some of the power and limitations of the low-level visual preattentive mechanisms that carry out massively parallel processing of our current visual field. However, human memory for things that are not directly visible is notoriously limited. These limits come into play not only for long-term recall but also for shorter-term working memory, both visual and nonvisual. We store surprisingly little information internally in visual working memory, leaving us vulnerable to **change blindness**: the phenomenon where even very large changes are not noticed if we are attending to something else in our view [Simons 00].

► More aspects of memory and attention are covered in Section 6.5.

Display capacity is a third kind of limitation to consider. Vis designers often run out of pixels; that is, the resolution of the screen is not enough to show all desired information simultaneously. The **information density** of a single image is a measure of the amount of information encoded versus the amount of unused space.* Figure 1.6 shows the same tree dataset visually encoded three differ-

★ Synonyms for *information density* include **graphic density** and **data–ink ratio**.

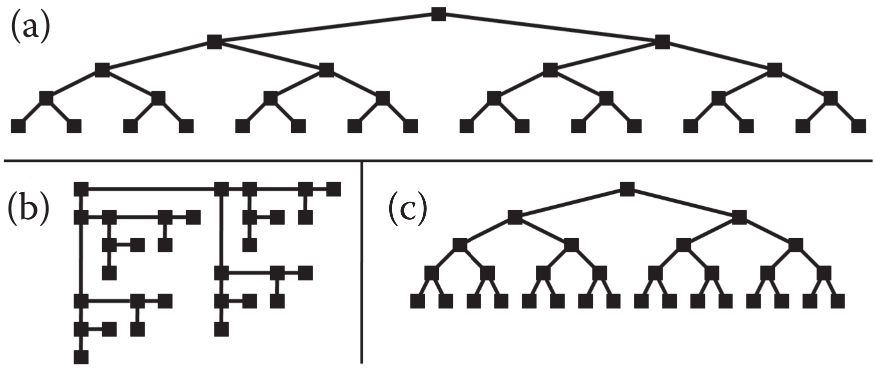


Figure 1.6. Low and high information density visual encodings of the same small tree dataset; nodes are the same size in each. (a) Low information density. (b) Higher information density, but depth in tree cannot be read from spatial position. (c) High information density, while maintaining property that depth is encoded with position. From [McGuffin and Robert 10, Figure 3].

ent ways. The layout in Figure 1.6(a) encodes the depth from root to leaves in the tree with vertical spatial position. However, the information density is low. In contrast, the layout in Figure 1.6(b) uses nodes of the same size but is drawn more compactly, so it has higher information density; that is, the ratio between the size of each node and the area required to display the entire tree is larger. However, the depth cannot be easily read off from spatial position. Figure 1.6(c) shows a very good alternative that combines the benefits of both previous approaches, with both high information density from a compact view and position coding for depth.

There is a trade-off between the benefits of showing as much as possible at once, to minimize the need for navigation and exploration, and the costs of showing too much at once, where the user is overwhelmed by visual clutter. The goal of idiom design choices is to find an appropriate balance between these two ends of the information density continuum.

1.14 Why Analyze?

This book is built around the premise that analyzing existing systems is a good stepping stone to designing new ones. When you're confronted with a vis problem as a designer, it can be hard to decide what to do. Many computer-based vis idioms and tools have

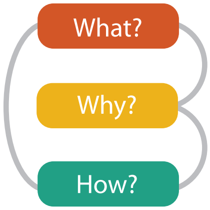


Figure 1.7. Three-part analysis framework for a vis instance: *why* is the task being performed, *what* data is shown in the views, and *how* is the vis idiom constructed in terms of design choices.

been created in the past several decades, and considering them one by one leaves you faced with a big collection of different possibilities. There are so many possible combinations of data, tasks, and idioms that it's unlikely that you'll find exactly what you need to know just by reading papers about previous vis tools. Moreover, even if you find a likely candidate, you might need to dig even deeper into the literature to understand whether there's any evidence that the tool was a success.

This book features an analysis framework that imposes a structure on this enormous design space, intended as a scaffold to help you think about design choices systematically. It's offered as a guide to get you started, not as a straitjacket: there are certainly many other possible ways to think about these problems!

Figure 1.7 shows the high-level framework for analyzing vis use according to three questions: **what** data the user sees, **why** the user intends to use a vis tool, and **how** the visual encoding and interaction idioms are constructed in terms of design choices. Each three-fold **what–why–how** question has a corresponding *data–task–idiom* answer trio. One of these analysis trios is called an **instance**.

► Chapter 2 discusses data and the question of *what*. Chapter 3 covers tasks and the question of *why*. Chapters 7 through 14 answer the question of *how* idioms can be designed in detail.

Simple vis tools can be fully described as an isolated analysis instance, but complex vis tool usage often requires analysis in terms of a sequence of instances that are chained together. In these cases, the chained sequences are a way to express dependencies. All analysis instances have the **input** of *what* data is shown; in some cases, **output** data is produced as a result of using the vis tool. Figure 1.8 shows an abstract example of a chained sequence, where the output of a prior instance serves as the input to a subsequent one.

The combination of distinguishing why from how and chained sequences allows you to distinguish between means and ends in

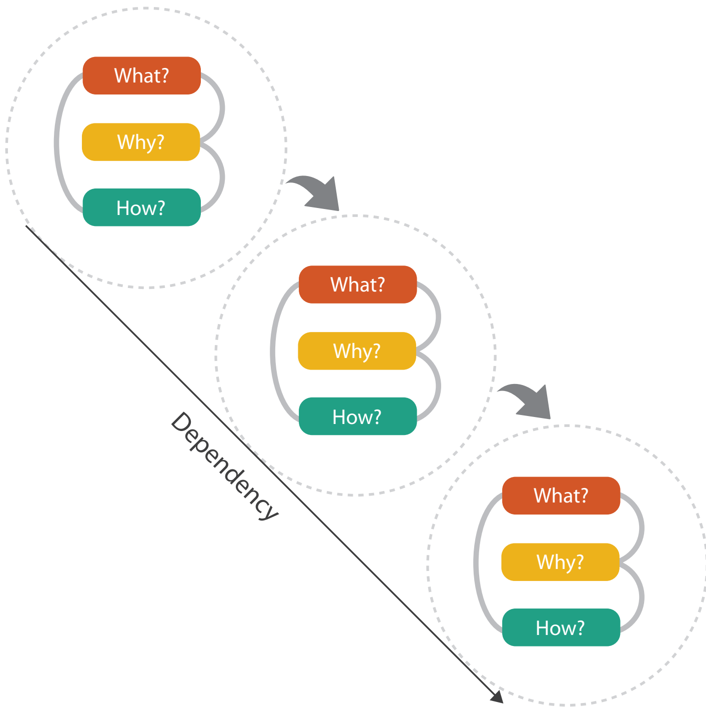


Figure 1.8. Analyzing vis usage as chained sequences of instances, where the output of one instance is the input to another.

your analysis. For example, a user could *sort* the items shown within the vis. That operation could be an end in itself, if the user's goal is to produce a list of items ranked according to a particular criterion as a result of an analysis session. Or, the sorting could be the means to another end, for example, finding outliers that do not match the main trend of the data; in this case, it is simply done along the way as one of many different operations.

1.15 Further Reading

Each Further Reading section provides suggestions for further reading about some of the ideas presented in the chapter and acknowledges key sources that influenced the discussion.

Why Use an External Representation? The role and use of external representations are analyzed in papers on the nature of external representations in problem solving [Zhang 97] and a representational analysis of number systems [Zhang and Norman 95]. The influential paper *Why A Diagram Is (Sometimes) Worth Ten Thousand Words* is the basis for my discussion of diagrams in this chapter [Larkin and Simon 87].

Why Show the Data in Detail? Anscombe proposed his quartet of illustrative examples in a lovely, concise paper [Anscombe 73]. An early paper on the many faces of the scatterplot includes a cogent discussion of why to show as much of the data as possible [Cleveland and McGill 84b].

What Is the Vis Design Space? My discussion of the vis design space is based on our paper on the methodology of design studies that covers the question of progressing from a loose to a crisp understanding of the user's requirements [Sedlmair et al. 12].

What Resource Limitations Matter? Ware's textbook provides a very thorough discussion of human limitations in terms of perception, memory, and cognition [Ware 13]. A survey paper provides a good overview of the change blindness literature [Simons 00].

The idea of information density dates back to Bertin's discussion of *graphic density* [Bertin 67], and Tufte has discussed the *data–ink ratio* at length [Tufte 83].

The Big Picture The framework presented here was inspired in part by the many taxonomies of data that have been previously proposed, including the synthesis chapter at the beginning of an early collection of infovis readings [Card et al. 99], a taxonomy that emphasizes the division between continuous and discrete data [Tory and Möller 04a], and one that emphasizes both data and tasks [Shneiderman 96].

Field Datasets Several books discuss the spatial field dataset type in far more detail, including two textbooks [Telea 07, Ward et al. 10], a voluminous handbook [Hansen and Johnson 05], and the *vtk* book [Schroeder et al. 06].

Attribute Types The attribute types of categorical, ordered, and quantitative were proposed in the seminal work on scales of measurement from the psychophysics literature [Stevens 46]. Scales of measurement are also discussed extensively in the book *The Grammar of Graphics* [Wilkinson 05] and are used as the foundational axes of an influential vis design space taxonomy [Card and Mackinlay 97].

Key and Value Semantics The Polaris vis system, which has been commercialized as Tableau, is built around the distinction between key attributes (independent dimensions) and value attributes (dependent measures) [Stolte et al. 02].

Temporal Semantics A good resource for time-oriented data vis is a recent book, *Visualization of Time-Oriented Data* [Aigner et al. 11].

The Big Picture An earlier version of the what–why–how framework was first presented as a paper [Brehmer and Munzner 13], which includes a very detailed discussion of its relationship to the extensive previous work in classifications of tasks and interaction idioms. That discussion covers 30 previous classifications and 20 relevant references, ranging from a characterization of the scientific data analysis process [Springmeyer et al. 92], to an influential low-level task classification [Amar et al. 05], to a taxonomy of tasks for network datasets [Lee et al. 06], to a recent taxonomy of interaction dynamics [Heer and Shneiderman 12].

Who: Designers versus Users Some of the challenges inherent in bridging the gaps between vis designers and users are discussed in an influential paper [van Wijk 06].

Derive Many vis pipeline models discuss the idea of data transformation as a critical early step [Card et al. 99, Chi and Riedl 98], and others also point out the need to transform between different attribute types [Velleman and Wilkinson 93]. A later taxonomy of vis explicitly discusses the idea that data types can change as the result of the transformation [Tory and Möller 04b].

Examples The analysis examples are SpaceTree [Plaisant et al. 02], TreeJuxtaposer [Munzner et al. 03], Strahler numbers for tree simplification [Auber 02], and linked derived spaces for feature detection [Henze 98].

The Big Picture I first presented the four-level nested model of vis design as a paper [Munzner 09a], with a discussion of blocks and guidelines between them in a follow-up paper [Meyer et al. 13]; both of these contain many more references to previous and related work. McGrath's analysis of the strengths and limitations of different experimental methods is well worth reading [McGrath 94], and it influenced my partition of validation techniques according to levels.

Problem-Driven Work A good entry point for problem-driven vis work is a detailed discussion of design study methodology, with a nine-stage framework for conducting them and suggestions for how to avoid 32 pitfalls [Sedlmair et al. 12]. Another framework for problem-driven work is the Multidimensional In-depth Long-term Case studies (MILC) approach, which also advocates working closely with domain users [Shneiderman and Plaisant 06].

Abstraction Level A recent paper argues that both data and task abstractions are important points of departure for vis designers [Pretorius and van Wijk 09]. The problems at the abstraction level fall into the realm of requirements elicitation and analysis in software engineering; a good starting point for that literature is a recent book chapter [Maalej and Thurimella 13].

Algorithm Level There are several existing books with a heavy focus on the algorithm level, including two textbooks [Telea 07, Ward et al. 10] and a large handbook [Hansen and Johnson 05]. Other options are recent survey papers on a particular topic, or specific research papers for very detailed discussion about a given algorithm. The larger issues of algorithm design are certainly not unique to vis; an excellent general reference for algorithms is a popular textbook that also covers complexity analysis [Cormen et al. 90].

Human–Computer Interaction A comprehensive textbook is a good starting point for the academic human–computer interaction literature [Sharp et al. 07]. A very accessible book is a good starting point for the large literature aimed at practitioners [Kuniavsky 03].

Evaluation Methods A book chapter provides an excellent survey and overview of evaluation and validation methods for vis, including an extensive discussion of qualitative methods [Carpendale 08]. Another discussion of evaluation challenges includes a call for more repositories of data and tasks [Plaisant 04]. A viewpoint article contains the thoughts of several researchers on why, how, and when to do user studies [Kosara et al. 03].

Field Studies For field studies, contextual inquiry is a particularly important method and is covered well in a book by one of its pioneers [Holtzblatt and Jones 93].

Experiment Design For lab studies, my current favorite references for experiment design and analysis are a cogent and accessible recent monograph [Hornbaek 13], a remarkably witty book [Field and Hole 03], and a new textbook with many examples featuring visualization [Purchase 12].

The Big Picture The highly influential theory of visual marks and channels was proposed by Bertin in the 1960s [Bertin 67]. The ranking of channel effectiveness proposed in this chapter is my synthesis across the ideas of many previous authors and does not come directly from any specific source. It was influenced by the foundational work on ranking of visual channels through measured-response experiments [Cleveland and McGill 84a], models [Cleveland 93a], design guidelines for matching visual channels to data type [Mackinlay 86], and books on visualization [Ware 13] and cartography [MacEachren 95]. It was also affected by the more recent work on crowdsourced judgements [Heer and Bostock 10], taxonomy-based glyph design [Maguire et al. 12], and glyph design in general [Borgo et al. 13].

Psychophysical Measurement The foundational work on the variable distinguishability of different visual channels, the categorization of channels as metathetic identity and prothetic magnitude, and scales of measurement was done by a pioneer in psychophysics [Stevens 57, Stevens 75].

Effectiveness and Expressiveness Principles The principles of expressiveness for matching channel to data type and effectiveness for choosing the channels by importance ordering appeared in a foundational paper [Mackinlay 86].

Perception This chapter touches on many perceptual and cognitive phenomena, but I make no attempt to explain the mechanisms that underlie them. I have distilled an enormous literature down to the bare minimum of what a beginning vis designer needs to get started. The rich literature on perception and cognitive phenomena is absolutely worth a closer look, because this chapter only scratches the surface; for example, the Gestalt principles are not covered.

Ware offers a broad, thorough, and highly recommended introduction to perception for vis in his two books [Ware 08, Ware 13]. His discussion includes more details from nearly all of the topics in this chapter, including separability and popout. An overview of the literature on popout and other perceptual phenomena appears on a very useful page that includes interactive demos http://www.csc.ncsu.edu/faculty/healey/PP [Healey 07]; one of the core papers in this literature begins to untangle what low-level features are detected in early visual processing [Treisman and Gormican 88].

No Unjustified 3D The differences between planar and depth spatial perception and the characteristics of 3D depth cues are discussed at length in both of Ware's books [Ware 08, Ware 13]. An in-depth discussion of the issues of 2D versus 3D [St. John et al. 01] includes references to many previous studies in the human factors and air traffic control literature including the extensive work of Wickens. Several careful experiments overturned previous claims of 3D benefits over 2D [Cockburn and McKenzie 00, Cockburn and McKenzie 01, Cockburn and McKenzie 04].

Memory Ware's textbook is an excellent resource for memory and attention as they relate to vis [Ware 13], with much more detail than I provide here. A recent monograph contains an interesting and thorough discussion of supporting and exploiting spatial memory in user interfaces [Scarr et al. 13].

Animation An influential paper on incorporating the principles of hand-drawn animation into computer graphics discusses the importance of choreography to guide the viewer's eyes during narrative storytelling [Lasseter 87]. A meta-review of animation argues that many seemingly promising study results are confounded by attempts to compare incommensurate situations; the authors find that small multiples are better than animation if equivalent information is shown [Tversky et al. 02] and the segmentation is carefully chosen [Zacks and Tversky 03]. An empirical study found that while trend animation was fast and enjoyable when used for presentation it did lead to errors, and it was significantly slower than both small multiples and trace lines for exploratory analysis [Robertson et al. 08].

Change Blindness A survey paper is a good starting point for the change blindness literature [Simons 00].

Overview, Zoom and Filter, Details on Demand This early and influential mantra about overviews is presented in a very readable paper [Shneiderman 96]. More recently, a synthesis review analyzes the many ways that overviews are used in infovis [Hornbæk and Hertzum 11].

Responsiveness Is Required Card pioneered the discussion of latency classes for vis and human–computer interaction [Card et al. 91]; an excellent book chapter covering these ideas appears in a very accessible book on interface design [Johnson 10, Chapter 12]. The costs of interaction are discussed in a synthesis review [Lam 08] and a proposed framework for interaction [Yi et al. 07].

Get It Right in Black and White A blog post on Get It Right in Black and White is a clear and concise starting point for the topic [Stone 10].

Function First, Form Next A very accessible place to start for basic graphic design guidelines is *The Non-Designer's Design Book* [Williams 08].

The Big Picture Many previous authors have proposed ways to categorize vis idioms. My framework was influenced by many of them, including an early taxonomy of the infovis design space [Card and Mackinlay 99] and tutorial on visual idioms [Keim 97], a book on the grammar of graphics [Wilkinson 05], a taxonomy of multidimensional multivariate vis [McGuffin 14], papers on generalized pair plots [Emerson et al. 12] and product plots [Wickham and Hofmann 11], and a recent taxonomy [Heer and Shneiderman 12]. Bertin's very early book *Semiology of Graphics* has been a mother lode of inspiration for the entire field and remains thought provoking to this day [Bertin 67].

History The rich history of visual representations of data, with particular attention to statistical graphics such as time-series line chart, the bar chart, the pie chart, and the circle chart, is documented at the extensive web site http://www.datavis.ca/milestones [Friendly 08].

Statistical Graphics A book by statistician Bill Cleveland has an excellent and extensive discussion of the use of many traditional statistical charts, including bar charts, line charts, dot charts, and scatterplots [Cleveland 93b].

Stacked Charts The complex stacked charts idiom of streamgraphs was popularized with the ThemeRiver system [Havre et al. 00]; later work analyzes their geometry and asthetics in detail [Byron and Wattenberg 08].

Bar Charts versus Line Charts A paper from the cognitive psychology literature provides guidelines for when to use bar charts versus line charts [Zacks and Tversky 99].

Banking to 45 Degrees Early work proposed aspect ratio control by banking to 45° [Cleveland et al. 88, Cleveland 93b]; later work extended this idea to an automatic multiscale framework [Heer and Agrawala 06].

Heatmaps and Matrix Reordering One historical review covers the rich history of heatmaps, cluster heatmaps, and matrix reordering [Wilkinson and Friendly 09]; another covers matrix reordering and seriation [Liiv 10].

Parallel Coordinates Parallel coordinates were independently proposed at the same time by a geometer [Inselberg and Dimsdale 90, Inselberg 09] and a statistician [Wegman 90].

Radial Layouts Radial layouts were characterized through empirical user studies [Diehl et al. 10] and have also been surveyed [Draper et al. 09].

Dense Layouts Dense layouts have been explored extensively for many datatypes [Keim 00]. The SeeSoft system was an early dense layout for text and source code [Eick et al. 92]; Tarantula is a later system using that design choice [Jones et al. 02].

History Thematic cartography, where statistical data is overlaid on geographic maps, blossomed in the 19th century. Choropleth maps, where shading is used to show a variable of interest, were introduced, as were dot maps and proportional symbol maps. The history of thematic cartography, including choropleth maps, is documented at the extensive web site http://www.datavis.ca/milestones [Friendly 08].

Cartography A more scholarly but still accessible historical review of thematic cartography is structured around the ideas of marks and channels [MacEachren 79]; MacEachren's full-length book contains a deep analysis of cartographic representation, visualization, and design with respect to both cognition and semiotics [MacEachren 95]. Slocum's textbook on cartography is a good general reference for the vis audience [Slocum et al. 08].

Spatial Fields One overview chapter covers a broad set of spatial field visual encoding and interaction idioms [Schroeder and Martin 05]; another covers isosurfaces and direct volume rendering in particular [Kaufman and Mueller 05].

Isosurfaces Edmond Halley presented isolines in 1686 and contour plots in 1701. The standard algorithm for creating isosurfaces is Marching Cubes, proposed in 1987 [Lorensen and Cline 87]; a survey covers some of the immense amount of followup work that has occurred since then [Newman and Yi 06]. Flexible isosurfaces are discussed in a paper [Carr et al. 04].

Direct Volume Rendering The *Real-Time Volume Graphics* book is an excellent springboard for further investigation of direct volume rendering [Engel et al. 06]. The foundational algorithm papers both appeared in 1988 from two independent sources: Pixar [Drebin et al. 88], and UNC Chapel Hill [Levoy 88]. The Simian system supports multidimensional transfer function construction [Kniss 02, Kniss et al. 05].

Vector Fields An overview chapter provides a good introduction to flow vis [Weiskopf and Erlebacher 05]. A series of state-of-the-art reports provide more detailed discussion of three flow vis idioms families: geometric [McLouglin et al. 10], texture based [Laramee et al. 04], and feature based [Post et al. 03]. The foundational algorithm for texture-based flow vis is Line Integral Convolution (LIC) [Cabral and Leedom 93].

Tensor Fields The edited collection *Visualization and Processing of Tensor Fields* contains 25 chapters on different aspects of tensor field vis, providing a thorough overview [Weickert and Hagen 06]. One of these chapters is a good introduction to diffusion tensor imaging in particular [Vilanova et al. 06], including a comparison between ellipsoid tensor glyphs and superquadric tensor glyphs [Kindlmann 04].

Network Layout An early survey of network vis [Herman et al. 00] was followed by one covering more recent developments [von Landesberger et al. 11]. A good starting point for network layout algorithms is a tutorial that covers node–link, matrix, and hybrid approaches, including techniques for ordering the nodes [McGuffin 12]. An analysis of edge densities in node–link graph layouts identifies the limit of readability as edge counts beyond roughly four times the node count [Melançon 06].

Force-Directed Placement Force-directed placement has been heavily studied; a good algorithmically oriented overview appears in a book chapter [Brandes 01]. The Graph Embedder (GEM) algorithm is a good example of a sophisticated placement algorithm with built-in termination condition [Frick et al. 95].

Multilevel Network Layout Many multilevel layouts have been proposed, including sfdp [Hu 05], FM^3 [Hachul and Jünger 04], and TopoLayout [Archambault et al. 07b].

Matrix versus Node–Link Views The design space of matrix layouts, node–link layouts, and hybrid combinations were considered for the domain of social network analysis [Henry and Fekete 06, Henry et al. 07]. The results of an empirical study were used to characterize the uses of matrix versus node–link views for a broad set of abstract tasks [Ghoniem et al. 05].

Design Space of Tree Drawings A hand-curated visual bibliography of hundreds of different approaches to tree drawing is available at http://treevis.net [Schulz 11]. Design guidelines for a wide variety of 2D graphical representations of trees are the result of analyzing their space efficiency [McGuffin and Robert 10]. Another analysis covers the design space of approaches to tree drawing beyond node–link layouts [Schulz et al. 11].

Treemaps Treemaps were first proposed at the University of Maryland [Johnson and Shneiderman 91]. An empirical study led to perceptual guidelines for creating treemaps by identifying the data densities at which length-encoded bar charts become less effective than area-encoded treemaps [Kong et al. 10].

The Big Picture Ware's textbook is an excellent resource for further detail on all of the channels covered in this chapter [Ware 13].

Color Theory Stone's brief article [Stone 10] and longer book [Stone 03] are an excellent introduction to color.

Colormap Design The design of segmented colormaps has been extensively discussed in the cartographic literature: Brewer offers very readable color use guidelines [Brewer 99] derived from that community, in conjunction with the very useful ColorBrewer tool at http://www.colorbrewer2.org. Early guidelines on quantitative colormap creation and the reasons to avoid rainbow colormaps are in series of papers [Bergman et al. 95, Rogowitz and Treinish 96, Rogowitz and Treinish 98], with more recent work continuing the struggle against rainbows as a default [Borland and Taylor 07]. An empirical study of bivariate colormaps showed their serious limitations for encoding two categorical attributes [Wainer and Francolini 80].

Motion An empirical study investigated different kinds of motion highlighting and confirmed its effectiveness in contexts where color coding was already being used to convey other information [Ware and Bobrow 04].

Texture Ware proposes breaking down texture into orientation, scale, and constrast subchannels, as part of a thorough discussion of the use of texture for visual encoding in his textbook [Ware 13, Chapter 6].

Change An early paper argues for adding interaction support to previously static visual encoding idioms as a good starting point for thinking about views that change [Dix and Ellis 98].

Animated Transitions A taxonomy of animated transition types includes design guidelines for constructing transitions, and an empirical study showing strong evidence that properly designed transitions can improve graphical perception of changes [Heer and Robertson 07].

Select The entertainingly named *Selection: 524,288 Ways to Say "This Is Interesting"* contains nicely reasoned arguments for narrowing selection operations across linked views to a small set of combinations [Wills 96].

Semantic Zooming The Pad++ system was an early exploration into semanic zooming [Bederson and Hollan 94]; LiveRAC is a more recent system using that idiom [McLachlan et al. 08].

Constrained Navigation Early work evangelized the idea of constrained navigation in 3D [Mackinlay et al. 90]; later work provides a framework for calculating smooth and efficient 2D panning and zooming trajectories [van Wijk and Nuij 03].

The Big Picture An extensive survey discusses many idioms that use the design choices of partitioning into multiple views, superimposing layers, changing the viewpoint through navigation, and embedding focus into context, and includes an assessment of the empirical evidence on their strengths and weaknesses [Cockburn et al. 08]. A monograph also presents an extensive discussion of the trade-offs between these design choices and guidelines for when and how to use them [Lam and Munzner 10]. A more specific paper quantifies costs and benefits of multiple views versus navigation within a single view for visual comparisons at multiple scales [Plumlee and Ware 06].

A thoughtful discussion of the design space of "composite vis" proposes the categories of juxtapose views side by side, superimpose views on top of each other, overload views by embedding, nest one view inside another, and integrate views together with explicit link marks between them [Javed and Elmqvist 12]. Another great discussion of approaches to comparison identifies juxtapose, superimpose and encode with derived data [Gleicher et al. 11].

Coordinating Juxtaposed Views A concise set of guidelines on designing multiple-view systems appears in an early paper [Baldonado et al. 00], and many multiple-view idioms are discussed in a later surveys [Roberts 07]. The Improvise toolkit supports many forms of linking between views [Weaver 04], and follow-on work has explored in depth the implications of designing coordinated multiple view systems [Weaver 10].

Partitioning The HiVE system supports flexible subdivision of attribute hierarchies with the combination of interactive controls and a command language, allowing systematic exploration of the design space of partitioning [Slingsby et al. 09], with spatially ordered treemaps as one of the layout options [Wood and Dykes 08].

Glyphs A recent state of the art report on glyphs is an excellent place to start with further reading [Borgo et al. 13]; another good overview of glyph design in general appears in a somewhat earlier handbook chapter [Ward 08]. The complex and subtle issues in the design of both macroglyphs and microglyphs are discussed extensively Chapters 5 and 6 of Ware's vis textbook [Ware 13]. Glyph placement in particular is covered a journal article [Ward 02]. The space of possible glyph designs is discussed from a quite different point of view in a design study focused on biological experiment workflows [Maguire et al. 12]. Empirical experiments on visual channel use in glyph design are discussed in a paper on color enhanced star plot glyphs [Klippel et al. 09].

Linked Highlighting Linked highlighting was proposed at Bell Labs, where it was called *brushing* [Becker and Cleveland 87]; a chapter published 20 years later contains an in-depth discussion following up these ideas [Wills 08].

Superimposing Layers A concise and very readable blog post discusses layer design and luminance constrast [Stone 10]. Another very readable article discusses the benefits of superimposed dot charts compared to grouped bar charts [Robbins 06].

Filtering Early work in dynamic queries popularized filtering with tightly coupled views and extending standard widgets to better support these queries [Ahlberg and Shneiderman 94].

Scented Widgets Scented widgets [Willett et al. 07] allude to the idea of information scent proposed within the theory of information foraging from Xerox PARC [Pirolli 07].

Boxplots The boxplot was originally proposed by Tukey and popularized through his influential book on *Exploratory Data Analysis* [Tukey 77]. A recent survey paper discusses the many variants of boxplots that have been proposed in the past 40 years [Wickham and Stryjewski 12].

Hierarchical Aggregation A general conceptual framework for analyzing hierarchical aggregation is presented in a recent paper [Elmqvist and Fekete 10]. Earlier work presented hierarchical parallel coordinates [Fua et al. 99].

Spatial Aggregation The Modifiable Areal Unit Problem is covered in a recent handbook chapter [Wong 09]; a seminal booklet lays out the problem in detail [Openshaw 84]. Geographically weighted interactive graphics, or geowigs for short, support exploratory analysis that explicitly takes scale into account [Dykes and Brunsdon 07].

Attribute Reduction DOSFA [Yang et al. 03a] is one of many approaches to attribute reduction from the same group [Peng et al. 04, Yang et al. 04, Yang et al. 03b]. The DimStiller system proposes a general framework for attribute reduction [Ingram et al. 10]. An extensive exploration of similarity metrics for dimensional aggregation was influential early work [Ankerst et al. 98].

Dimensionality Reduction The foundational ideas behind multidimensional scaling were first proposed in the 1930s [Young and Householder 38], then further developed in the 1950s [Torgerson 52]. An early proposal for multidimensional scaling (MDS) in the vis literature used a stochastic force simulation approach [Chalmers 96]. The Glimmer system exploits the parallelism of graphics hardware for MDS; that paper also discusses the history and variants of MDS in detail [Ingram et al. 09]. Design guidelines for visually encoding dimensionally reduced data suggest avoiding the use of 3D scatterplots [Sedlmair et al. 13].

The Big Picture Two extensive surveys discuss a broad set of idioms that use the choices of changing the viewpoint through navigation, partitioning into multiple views, and embedding focus into context, including an assessment of the empirical evidence on the strengths and weaknesses of these three approaches and guidelines for design [Cockburn et al. 08, Lam and Munzner 10].

Early Work Early proposals for focus+context interfaces were the Bifocal Display [Spence and Apperley 82] and polyfocal cartography [Kadmon and Shlomi 78]. An early taxonomy of distortion-based interfaces introduced the unifying vocabulary of magnification and transformation functions [Leung and Apperley 94].

Fisheye Views The fundamental idea of generalized fisheye views [Furnas 82, Furnas 86] was followed up 20 years later with a paper questioning the overwhelming emphasis on geometric distortion in the work of many others in the intervening decades [Furnas 06].

3D Perspective Influential 3D focus+context interfaces from Xerox PARC included the Perspective Wall [Mackinlay et al. 91] and Cone Trees [Robertson et al. 91].

Frameworks Two general frameworks for focus+context magnification and minimization are elastic presentation spaces [Carpendale et al. 95, Carpendale et al. 96] and nonlinear magnification fields [Keahey and Robertson 97].

Hyperbolic Geometry Hyperbolic 2D trees were proposed at Xerox PARC [Lamping et al. 95] and 3D hyperbolic networks were investigated at Stanford [Munzner 98].

Stretch and Squish Navigation The TreeJuxtaposer system proposed the guaranteed visibility idiom and presented algorithms for stretch and squish navigation of large trees [Munzner et al. 03], followed by the PRISAD framework that provided further scalability and handled several data types [Slack et al. 06].

Graph-Theoretic Scagnostics Scagnostics builds on ideas originally proposed by statisticians John and Paul Tukey [Wilkinson et al. 05, Wilkinson and Wills 08].

VisDB The VisDB system was an early proposal of dense displays for multidimensional tables [Keim and Kriegel 94].

Hierarchical Clustering Explorer Different aspects of the Hierarchical Clustering Explorer system are described in a series of papers [Seo and Shneiderman 02, Seo and Shneiderman 05].

PivotGraph The PivotGraph system visually encodes a different derived data abstraction than most network vis idioms [Wattenberg 06].

InterRing The InterRing system supports hierarchy exploration through focus+context interaction with geometric distortion and multiple foci. [Yang et al. 02].

Constellation The Constellation system supports browsing a complex multilevel network with a specialized layout and dynamic layering [Munzner et al. 99, Munzner 00].

[Auber et al. 12] David Auber, Daniel Archambault, Romain Bourqui, Antoine Lambert, Morgan Mathiaut, Patrick Mary, Maylis Delest, Jonathan Dubois, and Guy Melançon. "The Tulip 3 Framework: A Scalable Software Library for Information Visualization Applications Based on Relational Data." Technical report, INRIA Research Report 7860, 2012. *(pages 371, 372, 373)*

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