

This is my master's thesis written for the department of Technical Communication at the University of Washington, 2006.

Please feel free to send me any thoughts, feedback, or questions.

Thank you, Noah Iliinsky

[iliinsky@gmail.com](mailto:iliinsky@gmail.com)

Generation of Complex Diagrams:  
How to Make Lasagna Instead of Spaghetti

Noah P. N. Iliinsky

A thesis  
submitted in partial fulfillment of the  
requirements for the degree of

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Technical Communication

University of Washington  
Graduate School

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Noah P. N. Iliinsky

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examining committee have been made.

Committee Members:

---

David Farkas

---

Thomas Williams

---

William Winn

Date: \_\_\_\_\_

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**Abstract**

Generation of Complex Diagrams:  
How to Make Lasagna Instead of Spaghetti

Noah P. N. Iliinsky

Chair of the Supervisor Committee:

Professor David Farkas

Technical Communication

This thesis presents a system for the generation of complex diagrams. “Complexity” is defined as a measure of distinct data types that are independently visually encoded. Diagrams representing four or more types of data are defined as complex, while diagrams representing three or fewer are simple. Successful generation of complex diagrams is dependent on appropriate design choices. Five fundamental principles are introduced to guide the choices made by the diagram designer. The two contextual fundamental principles are “different goals require different methods,” addressing the needs of the diagram designer, and “audience brings context with them,” addressing the needs and context of the diagram reader. The three perceptual fundamental principles are the “principle of information availability,” which guides the selection and density of the diagram elements, the “principle of semantic distance,” which guides the spatial placement and grouping of the diagram elements, and the “principle of informative changes,” which guides the visual encoding of the diagram elements. A review of the diagram design process, comprising selection, encoding, and placement of the diagram components, is given. For each phase of the design process the influence of the appropriate fundamental principles is discussed, and the fundamental principles are extended into applied guidelines and suggestions.

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## PREFACE

As with most inspiration, the subtitle of this thesis came to me in a moment of remarkable lucidity. My advisor, Professor David Farkas, and I had a conversation in which we made multiple references to “spaghetti diagrams”: diagrams which have undefined axes, little or no order, and are a hodgepodge of similar elements (Figure 22, Entity Relationship Diagram, for example). The next afternoon I realized that the diagrams I was advocating had many different types of entities, were multi-layered, and well ordered: I was making lasagna diagrams! I have since found this metaphor to be quite useful, as it is both instructive and humorous. As such, it has earned a place in the title of my thesis.

## **ACKNOWLEDGEMENTS**

It is impossible to properly list everyone who contributed to my experience of writing this thesis. Thank you, to all of my friends who have known me while I worked on this project, encouraged me, fed me, offered rides and loaned me cars, hosted pho, understood when I disappeared for months, offered study breaks and company, offered opinions and feedback, and asked good questions about my work.

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None of this would have been possible without my amazing advisor, Dave Farkas. He nudged me to write a thesis, offered just the right amount of guidance, asked the perfect questions, and gently tossed out suggestions that have been incredibly useful.

And of course, huge thanks goes out to all my family, who has always supported my endeavors, encouraged me, and checked in when I didn't call.

Thank you all.

## **DEDICATION**

To my parents, who taught me how to make good choices,  
and  
to my grandparents, who taught me not to fear living an interesting life.

## Introduction

Diagrams have been used for centuries (Minard, 1861; Tufte, 1983) to convey all manner of information, including both quantitative and qualitative data types, frequently in combination. Diagrams are often used to efficiently show a wide variety of knowledge and interaction types, relying on visual and spatial encodings to reveal the relationships among the elements (Gattis, 2003; Tversky, 2001). Diagrams are “well-suited to illustrate intercomponent relationships and sequences (Winn, 1991, p. 240), and are particularly useful for representing logical and complex interactions among entities (Martin and McClure, 1984). Mayer (1989) demonstrated that appropriate combinations of visuals and text were more effective at conveying knowledge than either alone, and Winn and Holliday (1982) claim that “diagrams can be an extremely powerful medium provided they are properly designed and used” (p. 277).

Despite the evidence supporting the benefits of good diagrams with non-trivial encodings, “the vast majority of … diagrams currently in use are very simple. … They are often poor at showing the types of entities and the types of relationships,” and typically reveal attributes by using text labels, rather than visual encoding (Ware, 2004, p. 213-215).

This thesis attempts to address those issues on two fronts. First, I propose a system for quantifying the “dimensions of complexity” of a diagram: by this I mean the number of discrete types of information that are visually encoded in a diagram. The motivation for this quantification is to recognize that greater-than-average quantities of information can be made readily available in a good diagram. The definition of dimensions of complexity gives a concrete vocabulary to that conversation, and allows for comparisons and quantitative evaluations of the knowledge content of diagrams.

Second, I propose that good diagrams with better-than-average complexity can be successfully constructed by referring to a set of basic and accessible contextual and perceptual fundamental principles. This thesis examines their implications, and clearly demonstrates how they inform the diagram design process. While most of the ramifications of these principles are relatively well known to psychologists, technical communicators, and graphic designers, they have not yet been bundled into a concise, coherent package that reviews the theory and dictates practice.

I present information here at a level that is accessible and relevant to readers with a range of experience. My intent is to convey enough knowledge and background to give the reader a quick, reliable rule-of-thumb reference, as well as to provide more detailed guidance if they need it. For example, a novice diagram designer might often read for specific implementation suggestions or ideas, whereas a more advanced author would occasionally use one of the principles to guide a particularly difficult or unclear choice. This degree of flexibility and breadth of coverage allows this system to be applicable to a variety of diagram types and contexts, from stand-alone information graphics, to in-context diagrams with a quantity of supporting text.

It is my hope that this system will allow more and better diagrams to be constructed, and will help make knowledge more accessible.

## Chapter 1: Diagrams and Complexity

### 1.1 Terminology: What is a diagram?

The focus of this thesis is the effective visual representation of qualitative information and relationships. Qualitative visuals usually take the form of charts, maps, or diagrams and represent entities or states and their connections or relationships. Flow charts, organization charts, and other charts are drawn using boxes and arrows. Network maps and knowledge maps, such as those by Horn, are built from nodes and links (or points and edges, or boxes and arrows). The term diagram is often used to refer to relatively representational, less abstract visuals, such as assembly diagrams. However, certain diagrams, such as sentence diagrams, can also be abstract.

For the purposes of this thesis the word “diagram” will be used to refer to any visual that is primarily a representation of qualitative relationships, including charts, maps, and diagrams as they are defined above. This usage is consistent with the field (e.g., Gattis, Martin & McClure, Robertson, Winn & Holliday, etc.). Illustrations of primarily quantitative relationships are generally called graphs and will be referred to as such here, and not included in my use of the word diagram. Tables that contain significant qualitative information may also be considered highly-ordered diagrams.

### 1.2 Terminology: What is meant by complexity?

#### 1.2.1 Definition of complexity

For the purposes of this thesis, the notion of complexity is used to refer to how many types of information and relationships are being represented visually. A diagram with few types of information is not very complex; one with many different types of information is more complex. It should be noted that my usage of complex is not a measure of the effort required to extract information

from the diagram, and in fact “‘complex’ suggests the unavoidable result of a necessary combining and does not imply fault or failure” (“complex”, 1993, p. 235). I will use the word “characteristic” to indicate something inherent to the data, and the word “property” to indicate a physical quality of the encoding.

### **1.2.2 Definition of complication**

Complexity should not be confused with complication, which is used here as a measure of how difficult it is to extract information from a diagram. The definition of complicated says that the term “applies to what offers great difficulty in understanding, solving, or explaining” (“complex”, 1993, p. 235). Complication is usually caused by a relatively large number of elements (nodes), a relatively large number of interrelationships (links), or particularly poor layout. A diagram may be both complex and complicated, either, or neither of these.

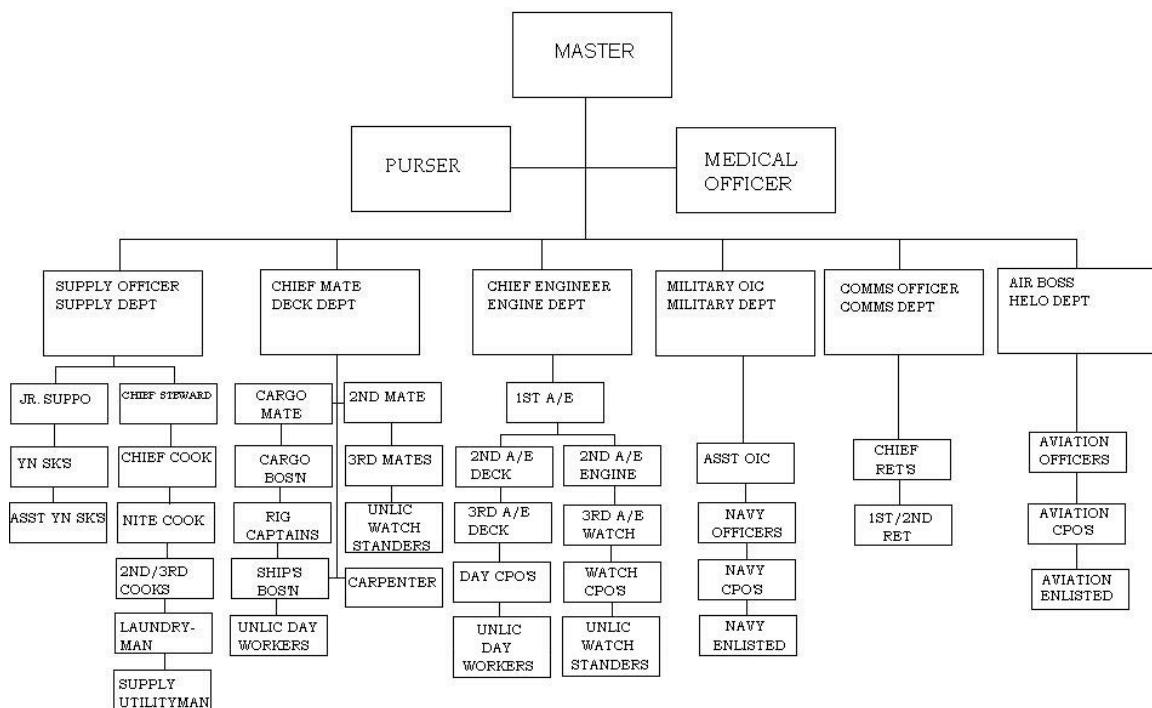
## **1.3 *Simple Diagrams***

Simple diagrams are more or less a solved problem. The design of some specific varieties of simple diagrams are well defined and well understood. Examples of these well-defined (and abundant) diagrams are organization charts, sentence diagrams, circuit diagrams, flow charts, product family maps, and network maps. However, all of these types of diagrams are limited, in that they usually represent no more than three types of information or relationships. Therefore, for the purposes of this thesis, any diagram that visually encodes three or fewer types of information is defined as a simple diagram. Here are some examples of simple diagrams.

### **1.3.1 Example: organization chart, not complex, not complicated**

This organization chart (Figure 1) visually contains between two and three kinds of information. The first consists of the boxes with the text data inside of

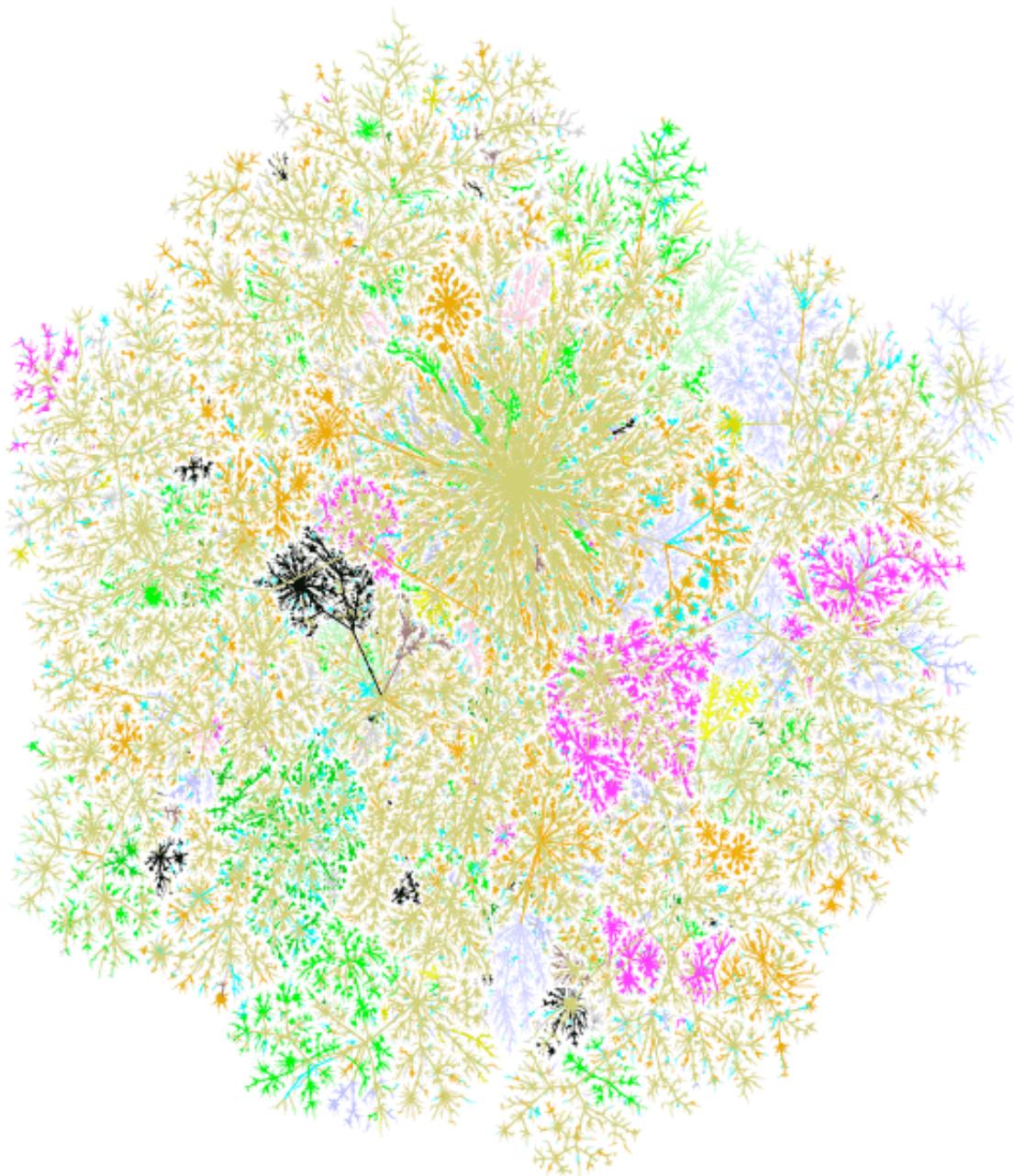
them. The second kind of information represented consists of the hierarchical relationships among the boxes (people). There is some information encoded in the size of the boxes, as the senior staff get larger boxes, but the effect of this encoding isn't consistent, as the size of the non-senior boxes vary with the amount of text in them. There is no other visual encoding present.



**Figure 1: Organization Chart (USNS Niagra Falls, n. d.)**

### 1.3.2 Example: map of the internet, not complex, but very complicated

The map of the internet (Figure 2) also encodes just two kinds of information. There are nodes that are identified only by color, and there are links among them. As with the organization chart, this diagram has two dimensions. Unlike the chart above, it is very complicated, in that there is a huge amount of data. Consequently, finding a specific point is very difficult.



**Figure 2: Map of the Internet (Cheswick, n. d.)**

## 1.4 *Complex Diagrams*

Complex diagrams, by my definition, encode and represent at least four types of information. This definition is based on the relatively large number of diagrams that contain three or fewer data types, and the relatively small number that contain four or more. Unlike the simple diagrams mentioned above, more complex diagrams are less common, are not well understood, and frequently are not very successful. Part of the reason for this is that we do not have widely known standards or conventions that describe the creation of complex diagrams. The lack of examples and conventions is the likely reason why most complex diagrams are not successful; that is, they are very difficult to extract information from.

There are two other fundamental factors that make complex diagrams difficult to execute well. One difficulty arises from dealing with more information than in a simple diagram, and one arises from dealing with qualitative information.

### 1.4.1 Why more complexity is difficult

The problem of diagram design is compounded when the diagram becomes complex, that is, when multiple characteristics need to be represented. Once an author chooses to use one visual property (e. g. color) to encode a particular characteristic (e. g. favorite flavor), any other use of that property (color) to encode any other characteristic (e.g. favorite sports team) increases the risk of confusion, not just within each characteristic, but also across unrelated characteristics. Once the most obvious encodings have been used, the author must venture into more subtle encodings to make their point. Clearly, the more characteristics there are to be represented, the more difficult this becomes.

### 1.4.2 Why qualitative relationships are difficult

The display of quantitative information is well understood. There are common metaphors for representing quantities in all different contexts, and most people are exposed to many examples every day. Quantitative visuals are found in the sports, weather, and business sections of the newspaper, on food packaging, and in advertising, to name just a few popular domains. There are standards for how quantities should be represented visually, and many books written about how to do it well (Brinton, 1917; Kosslyn, 1994; Tufte, 1983, 1990).

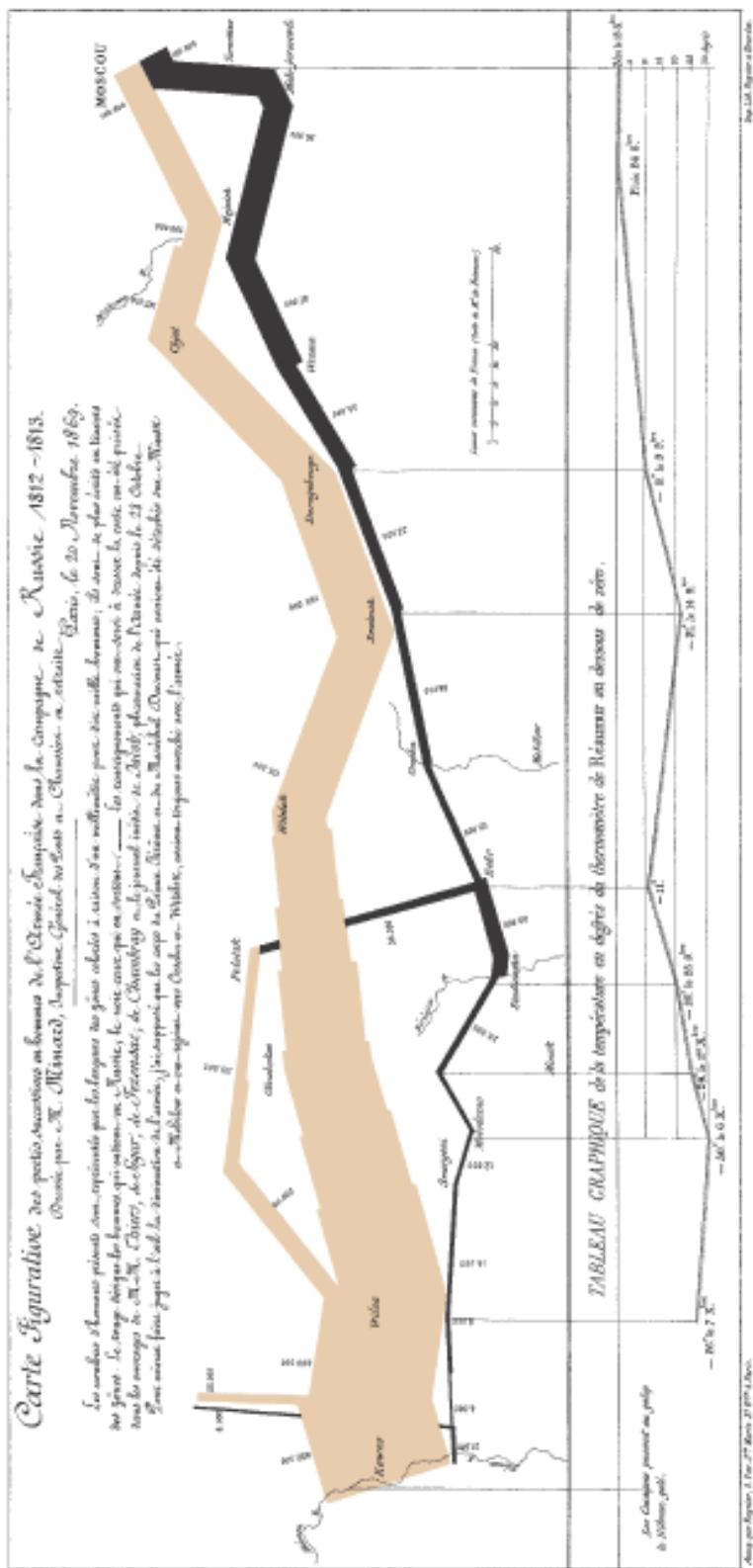
In the realm of qualitative relationships, those standards generally don't exist, or are not as well defined or absolute. This means that anyone who wants to show qualitative relationships frequently has to create the metaphor themselves, and do so in such a way that they can be comprehended by their audience. This can be a hard problem.

## 1.5 *Counting dimensions of complexity*

I define a “dimension of complexity” as a characteristic of the data that is visually encoded. The simple diagram examples mentioned above each have two types of visual encodings: the org chart has hierarchy and text encodings, and the internet map has color and connection encodings. To investigate more complexity, we'll now look at two good examples of complex diagrams. I'll demonstrate how to count dimensions of complexity, and discuss some factors that make them good diagrams.

### 1.5.1 Example: Minard showing seven dimensions of complexity

Tufte claims (1983, p. 40) that six variables are plotted in Minard's famous diagram of Napoleon's march to Moscow (Figure 3).



## Napoleon's March to Moscow The War of 1812

This classic of Charles Joseph Minard (1811–1870), the French engineer, shows the terrible fate of Napoleon's army in Russia. Described by E. J. Marey as seeming to "defy the gods of the Museum by its brutal eloquence," this combination of map and time-series, drawn in 1869, portrays the devastating losses suffered in Napoleon's Russian campaign of 1812. Beginning at the left on the Polish-Russian border near the Northern River, the black band shows the size of the army at each place on the map. In September, the army reached Moscow which was by then sacked, the army reached Moscow which was by then sacked and decimated, with less than 10,000 men. The path of Napoleon's retreat from Moscow is depicted by the dashed, broken band, which is linked to a temperature series and drawn at the bottom of the chart. It was a bitterly cold winter, and many froze on the march one of Banish. As the graphic shows, the crossing of the Berezina River was a disaster, and the army finally struggled back into Poland with only 10,000 men surviving. Also shown are the movements of auxiliary troops, as they would to protect the rear and the flank of the advancing army. Minard's graphic tells rich, sobering stories with its embroiling data, far more enlightening than the single number hovering along over time. See variables are plotted: the size of the army; its location on a two-dimensional surface; the direction of the army's movement; and transportation on various days during the retreat from Moscow. It may well be the best statistical graphic ever drawn.

Charles Joseph Minard  
Original Print: The Royal Library of Quantzana, Mysore

Reprint: Edward R. Tufte, The Visual Display of Quantitative Information

Figure 3: Losses of the French Army in Russia (Minard, 1861; Tufte, 1983)

1. army size (line width)
2. latitude (vertical position on the map)
3. longitude (horizontal position on the map)
4. direction of movement (continuity of the troop line from place to place)
5. temperatures (text and scale below the gallery, return trip only)
6. dates (text and scale below the gallery, return trip only)

Due to his focus on the quantitative characteristics of the diagram, Tufte neglects to mention what is perhaps the most obvious encoding in the diagram, a qualitative characteristic: on the way towards Moscow the line representing the size of the army is colored beige (shaded in some reproductions), and when returning home it is in black. I call Minard a diagram with seven dimensions of complexity.

Minard does a good job of using common quantitative metaphors (e.g., line size indicating army size) to convey knowledge. He takes full advantage of the placement on the page (in this case, the map) to represent spatial data. When other information is useful (dates, temperatures), he uses conventional encoding, and makes the associations among the places, dates, temperatures, and army size very clear. Finally, he makes the troop direction extremely clear, not by using arrows, but by using contrasting colors to indicate the two phases of the campaign. This last choice is excellent, because it does not rely on adding symbols (arrows) to clutter the image, but rather is an effect of the good choice Minard made previously in selecting the encoding of information that was already there (army size line).

### **1.5.2 Example: Mendeleev showing at least four levels of complexity**

A very common complex diagram is Mendeleev's periodic table of the elements, found in every science classroom and laboratory in the world. Even

the most basic periodic tables, such as Figure 4, will almost always encode at least four characteristics per element:

1. period (row)
  2. group (column)
  3. symbol
  4. atomic number

**Figure 4: Simple Periodic Table of the Elements (Periodic, n. d.)**

Beyond these four basic characteristics, a periodic table may encode any or all of the following:

5. state of matter (solid, liquid, gas)
  6. type (metal, noble gas, etc)
  7. radioactivity
  8. synthetic origin
  9. other text-encoded properties (name, mass, valence, etc)

Complexity is a measure of the number of non-redundant visual encoding methods used. For a periodic table, all of the text information, other than symbol and atomic number, is lumped together as one dimension of complexity. This is because most of the text-encoded information (listed under 9. above) is not easily visually differentiated: it's all text of similar visual impact.

However, the symbol and atomic number are not included in the “lump of text” dimension because of how they are presented and used. They are usually visually emphasized or differentiated to make them stand out from the balance of the text. The symbol for each element is frequently used as a label, rather than as a bit of text that is intended to be read as language to convey language-specific meaning. For example, “Au” is the symbol for the element gold; we don’t read Au as an abbreviation of the Latin “aurum” and then translate that to English; we simply know that in this context Au stands for gold. Similarly, while the atomic number is representative of a characteristic of the element (its number of protons), it is as commonly used as a unique label that identifies the element and also indicates its place in the ordered set of the table. The fact that gold has exactly 79 protons in its nucleus is usually less relevant than the fact that being element number 79 places it between platinum (78) and mercury (80).

The periodic table is an excellent example of the appropriate use of different encoding methods to reveal a large variety of both quantitative and qualitative characteristics in a way that is accessible. Like Minard, the periodic table uses the vertical and horizontal placement on the page to convey meaning. The periodic table uses inherently ordered properties (relative placement) to encode inherently ordered quantitative characteristics (period, group), and less ordered properties (color, shading) to encode qualitative characteristics (state of matter, metal/nonmetal, etc.). Finally, the periodic table uses

properties with relatively few differentiable variations (color) to represent characteristics with relatively few variations (state of matter), and properties with relatively many variations (numbers, symbols) to represent characteristics with relatively many variations (atomic number, name). These are all appropriate choices that allow each encoding to reveal data efficiently without overlapping the other encodings.

In contrast, consider attempting to encode the same information in other ways. Symbols (S, L, G) could easily be used to encode state of matter, but would be quickly lost among the other text in each element's cell. Color could be used to encode name, or atomic number, but decoding a particular shade to a value, or determining the relative or absolute order of more than 100 shades would be prohibitively difficult, unless the order of the elements was also encoded in another way, such as spatially. The lesson here is that the periodic table uses a wide variety of encoding styles (placement, symbol, fill and text color, text, etc.) and appropriately selects encodings that match the data to allow a very efficient transfer of knowledge.

### **1.5.3 Example: Wall Street Follies: incoherent complexity and complication**

The Wall Street Follies diagram (Figure 5) is a complex diagram executed less gracefully than the above two examples.

While there are a few uses of consistent encoding (various fines, some local groupings of players), there appears to be no system that informs global placement of nodes, use of color, use of line properties, use of text properties, selection of adjectives, or iconography. This diagram is effective in showing what a mess the whole business is, but beyond that, it's ineffective in conveying any real broad-scale knowledge to the reader.

I wouldn't attempt to count dimensions of complexity in this diagram, as the different types of information are not discrete. There is no way to clearly differentiate the flavors of what is being represented. Subjectively, I would call this diagram very complicated.

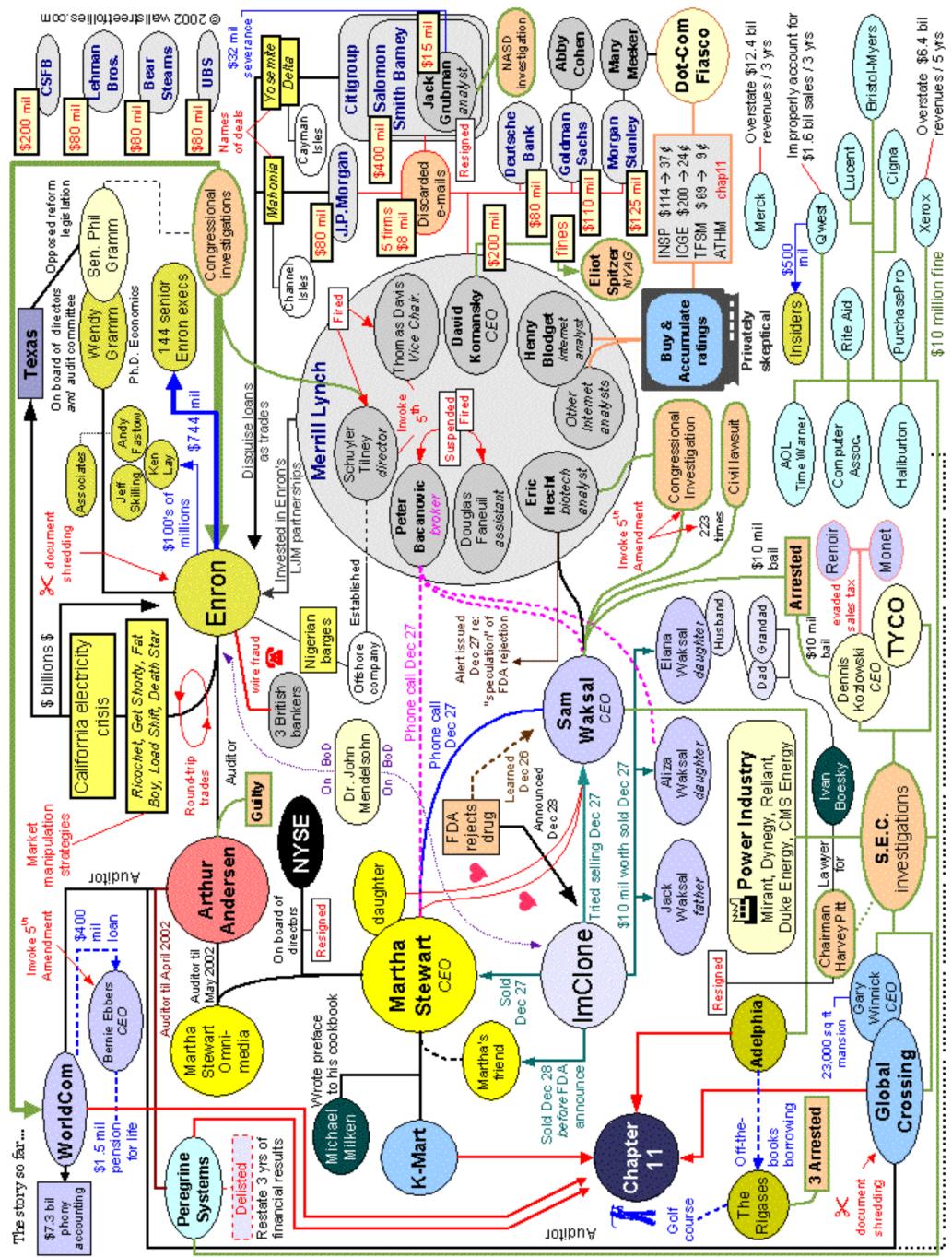


Figure 5: Wall Street Follies (Poyer, n. d.)

## Chapter 2: Motivation, Intention, and the Fundamental Principles

### 2.1 *Good choices based on sound principles*

This thesis proposes a system for generating high-quality diagrams. Specifically, it is designed to be especially useful for generating complex diagrams that include many types of information and many types of relationships, as the encoding challenges for both are similar. Rather than suggesting a specific set of rules to be followed to generate a specific type of diagram, this system proposes a general set of rules and guidelines to generate effective diagrams, regardless of context or content. In this way it is applicable to any context where the author chooses to generate a diagram and does not have a standard or convention to draw on. This is a broad problem, and it requires a broad approach.

Implicit in my analyses of good complex diagrams in section 1.5, is the claim that knowledge can be easily extracted from the diagrams because of good choices made by the authors. Suh believes that the design process “requires fundamental, correct principles and methodologies to guide *decision making in design*; otherwise, the ad hoc nature of design activities cannot be improved” (1990, p. 5). And Schön (1983) asserts that in situations where instinct or an ad hoc approach is insufficient to solve the problem at hand, experienced professionals succeed by entering into a mode of intentional, conscious problem solving. As discussed in section 1.4, the design of increasingly complex diagrams becomes more difficult and less solvable by ad hoc methods. I propose that as this difficulty in design increases, intentionality in the decision making process becomes more necessary.

The system proposed in this thesis helps diagram creators identify key choice points and then make good, informed design choices, using all of the graphical methods available. The system is grounded in the needs of the author and the reader, and in principles of human perception and cognition. All guidelines are based on those needs and fundamental principles.

## *2.2 The fundamental principles*

Contextual considerations:

1. Different communication goals require different methods
2. Audience brings context with them

Perceptual considerations:

3. The principle of information availability
4. The principle of semantic distance
5. The principle of informative changes

The balance of this thesis begins with a summary of the relevant theory behind each of the fundamental principles and discusses its consequences. Each choice point in the diagram generation process will be identified, and guidelines and examples relevant to that choice point will be discussed. This progression from fundamentals to specific examples will address the considerations authors face and help them generate superior diagrams.

## Chapter 3: Contextual Fundamental Principles

The contextual fundamental principles take into consideration the goals and needs of a diagram's author and reader. The effects and indications of these considerations are dynamic, and change with every diagram as the goals and audience change. These fundamental principles are especially relevant in the earlier, planning portions of the design process.

### 3.1 *Fundamental Principle: Different Goals Require Different Methods*

The first fundamental principle concerns authors and their reasons for designing diagrams. The goals that they aim to satisfy with the diagram can vary widely, even for ostensibly similar documents. Consider, for example, the differences in the content of a manual for operating a tool, versus the content of a manual for repairing that same tool. The operations manual will contain details about using particular functions and features that will not be in the repair manual, and the repair manual will contain instructions for testing, disassembly, and part replacement that will not be found in the operations manual.

While that example is simple, it serves to illustrate the importance of well defined goals for the document. "Almost everything ... in this world ... will be much more successful if [it] is designed for a realistic and clearly formulated purpose" (Farkas, 2002, p. 25). Well-defined goals guide the design process, and supply standards for success. Without well-defined goals, the author loses both of these benefits.

Once the goals are defined, the author must select implementations that fulfill the goals. "Design involves a continuous interplay between *what we want to achieve* and *how we want to achieve it*" (Suh, 1990, p. 25). The typical, obvious, or

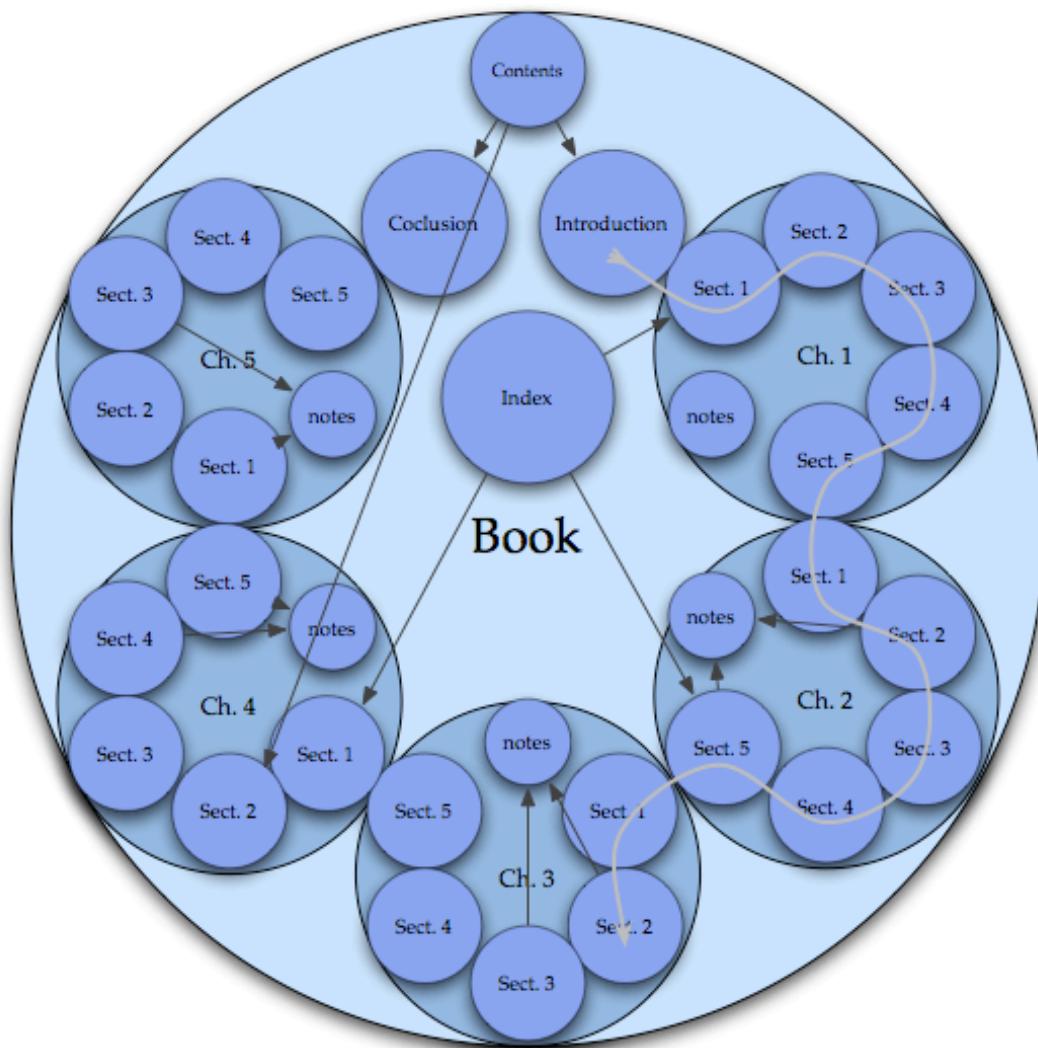
conventional representation of the information at hand may not be the best method to satisfy the actual goals of the diagram. Keeping the goals in mind helps the author make appropriate design choices.

### **3.1.1 Example: Book hierarchy diagram designed to show use**

A representation of a hierarchical structure typically takes the form of a tree (Brinton, 1917, p. 14-16; Horn, 1998, p. 127; Martin & McClure, 1984, p. 23-32; Robertson, 1988, p. 38-39), and shows the superordinate/subordinate relationships present, but generally not the other relationships that may exist among the nodes. This is the case in org charts (as in Figure 1: Organization Chart), genealogy charts, and other hierarchical classifications. However, when there are interesting relationships among the nodes, displaying them can be beneficial.

Figure 6, is a diagram that I designed to show not only the hierarchy, but also the typical use pattern of a book. Continuity in the book is indicated by contact of the circles. The reader's typical path is shown by the gray line, progressing in small and large clockwise arcs from section to section and chapter to chapter. The black arrows indicate some, but not all, possible non-linear paths that may be traveled by the reader as side trips, before they return to the main path. The goal of displaying the book's use, and not merely the hierarchy, has led to an atypical diagram that conveys more knowledge than the typical counterpart.

This diagram displays four dimensions of complexity: the identity of the nodes, the hierarchical relationships, the continuity between nodes in contact, and some possible paths between nodes. Without the arrows it loses a dimension of complexity. The use of color adds redundant encoding of the various hierarchy levels, but does not add to the complexity.



**Figure 6: Book Hierarchy (Iliinsky, 2003a)**

### 3.1.2 Example: Speech structure diagram designed to show threads and relationships

The public presentation of a speech (when unsupported by visual aids) is an interesting form of discourse because it contains little-to-no explicit structure. Typically, a speech is delivered (or read) with very few indications of

structure presented to the listener (or reader). Because they are designed to be spoken aloud and heard, there are no chapter titles or section headings in the text. At best, the speaker may pause to indicate a change of topic, or reveal a bit of structure by saying “now I’m going to talk about,” or, “let me give you an example.”

However, there is structure present in a speech. The speaker must present evidence or examples to support their goals, whether their goals are to persuade, inform, or entertain. They may also draw conclusions, ask relevant questions, or predict, all based on their evidence and conclusions. In order for the speech to be successful, the evidence, conclusions, and predictions must be logically tied together to build a coherent argument. In a well-crafted speech, the audience will have no trouble following the thread of the argument, despite the lack of explicit structure. However, if there is more than a small amount of content in the speech, the audience may not have the ability to rank the importance of various ideas, or even to identify the key concepts.

Figure 7 is a diagram I created of the first half of the speech *Viva Las Xmas* by Larry Harvey (2002), the founder of the Burning Man project. In the speech, he discusses some socioeconomic principles, and how they affect interactions between people in a marketplace economy, and also in the gift economy at Burning Man. The diagram uses placement, color, and links to show not only the chronology, hierarchical, and topical groupings of chunks of the speech, but also causality and conceptual connections among the chunks.

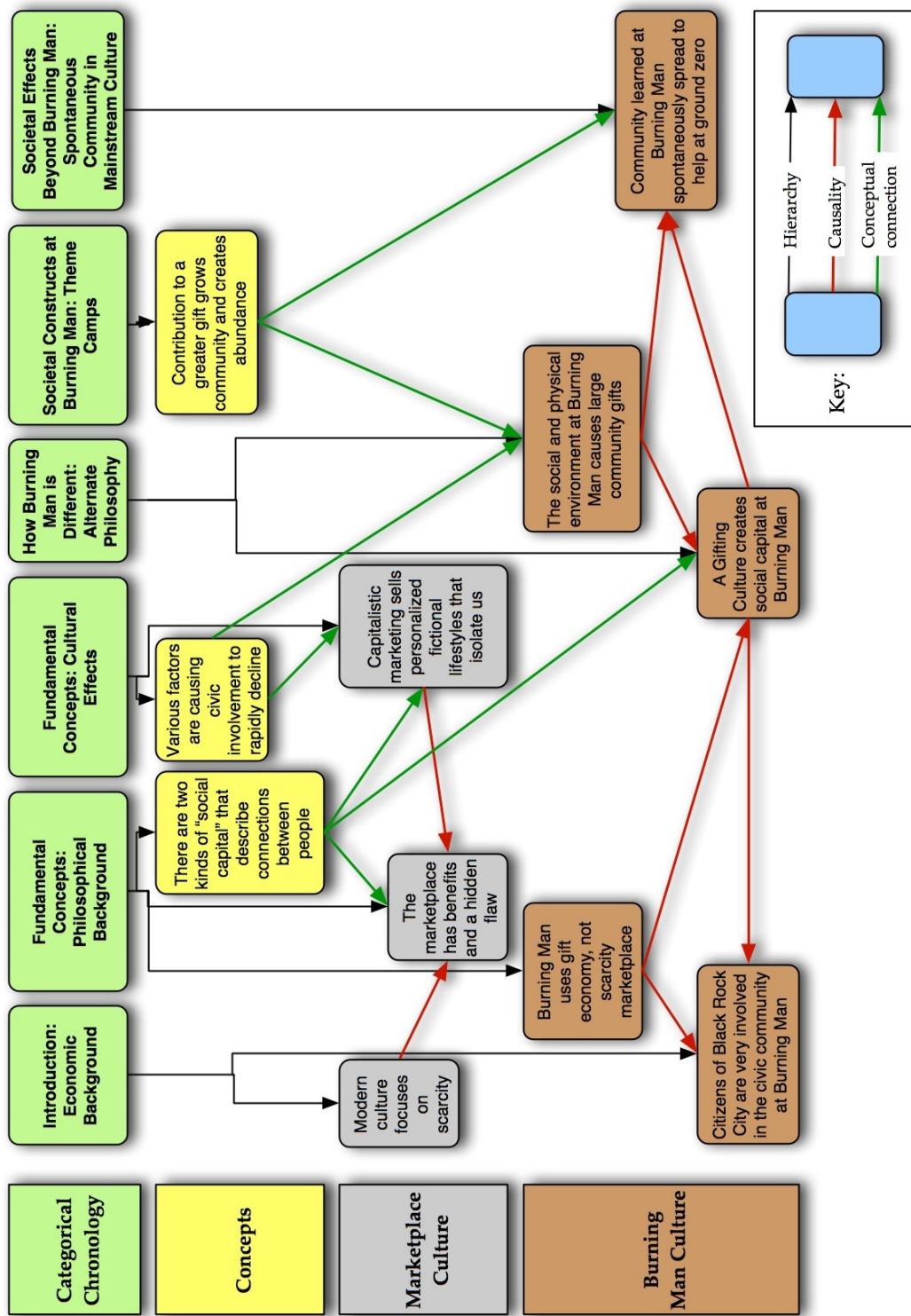


Figure 7: Harvey Speech showing threads (Iliinsky, 2003b)

This has some significant consequences. Not only does the diagram immediately reveal the topical threads in the speech, it also makes the important concepts clear by virtue of their relatively high number of links to other portions of the speech. The connections, relationships, and implications that are implicit in the speech become explicit in the diagram, thereby conveying more complete knowledge to the reader, reducing the amount of raw information that they have to integrate, and making the actual message of the speech more accessible. This type of diagram could be constructed before the presentation of a speech, and then used to support the speech as it was being delivered. This would enable the speech author to emphasize the key points and make the speech easier to follow.

This diagram reveals six dimensions of complexity.

1. hierarchical membership, indicated by the horizontal position below the green boxes and redundantly encoded with the vertical black arrows
2. topical grouping, indicated by the vertical position and redundantly encoded by color
3. specific chunk, indicated by the text in each box
4. chronological sequence, indicated by relative left to right position
5. causality, indicated by red arrows
6. conceptual connection, indicated by green arrows

### ***3.2 Fundamental Principle: Audience Brings Context with them***

Common sense would seem to dictate that, in virtually any medium, the audience must be considered when designing any communication. However, the degree to which the audience influences the interpretation of a communication is often underestimated. The needs, background, and biases of the audience are too-frequently ignored, discounted, or erroneously assumed to be similar to that of the document designer (Norman, 1990, p. 155) . Anyone

who has ever read a product manual can attest to this. Neglecting the audience's needs and biases can be a critical failure. In the following the terms "audience" and "reader" will be used more or less interchangeably.

### 3.2.1 The importance of context and schema

In their seminal paper, Bransford & Johnson (1972) show the role that context plays in comprehension. They find that readers who are provided with appropriate context before they are provided with content have much better comprehension and recall than readers who are not provided with any context. Further, they find that readers who are provided with context after the content perform much worse than those provided with context before content, and not much better than readers given no context at all. Clearly, providing context before content is beneficial to readers, and therefore should be considered by any designers interested in having their message retained by their readers.

Another notion relevant to learning and knowledge retention is "schema." Anderson & Pearson (1984) endorse a schema-based model of reading comprehension and recall. They claim that learning is the integration of new information into preexisting knowledge and belief structures, or schema (p. 255). In practical terms, learning is more than merely absorbing information; it is the ability of the reader to accurately recall and apply knowledge some time after it has been read (p. 278). Anderson & Pearson note that readers are more likely to accurately recall information that is compatible with their schemas, and that incompatible new information is eventually forgotten in favor of the original schema (p. 285).

These two points indicate that sufficient context is necessary for comprehension, and content that is compatible with existing schema will be retained better than content that is in conflict with existing schema. The

schema that Anderson and Pearson describe can be understood to function as an existing context that informs all of the learning done by an audience.

### **3.2.2 Accounting for context in the diagram**

Rather than attempting to create and present a context to support a diagram, a successful designer will instead create a diagram that relies on the context (and therefore schema) that are already in place in the readers' minds. If this is done effectively, the reader can still experience the learning benefits that result from an appropriate and sufficient context. If the designer does not take the reader's context into consideration, the reader's ability to comprehend, integrate, and recall the knowledge will be significantly impaired; this in turn proportionally impairs the designer's ability to succeed.

### **3.2.3 Three major considerations**

To achieve success, the designer must know what audience factors to consider. Kosslyn (1994) describes two varieties of audience schema or context. The first are the inherent characteristics of the entities and relationships being represented by the diagram. These might include relative size, relative placement, actual color, shape, native orientation, or other reader-identifiable visual characteristics. Kosslyn (1994) suggests "the properties of the visual pattern itself should reflect the properties of what is symbolized," and calls this notion "compatibility" (p. 8). These "can be called natural cognitive correspondences," says Tversky (2001, p. 95). Some of the spatial factors will also be addressed in my discussion of Semantic Distance.

There are also many learned contexts that influence interpretation. These influential contexts include regional, national, or ethnic origin, religion or political affinity, educational background, and profession or industry. Properties that may be subject to influence by learned context include languages spoken or industry jargon, left-right or top-bottom reading

precedence, the association of meaning with particular shapes or colors, and openness to particular ideas, just to name a few. Kosslyn (1994) calls these learned associations “cultural conventions,” and cautions that “if learned associations stored in memory [schema] conflict with the message of your [diagram], processing [learning and understanding] will be impaired” (38). Winn and Holliday (1982) demonstrated this effect by comparing the performance of readers given diagrams arranged in either conventional (left to right) or reversed (right to left) formats. Readers who viewed the conventional diagrams performed much better than those with reversed diagrams. Those with the reversed diagrams performed extremely poorly, at the level of those given no diagrams at all (pp. 287-289).

A final facet of reader context to consider is why the readers are reading the diagram. Their goals and reasons for reading the diagram, the time they have available to read and absorb the information, the level of understanding they need to achieve, and whether their reading is voluntary or compulsory should all be taken into consideration. These factors significantly affect the amount of time and effort readers will dedicate to understanding the diagram. If sufficient knowledge cannot be extracted within time and effort constraints, the reader will not be able to meet their needs and the designer will have failed.

### **3.2.4 Context's breadth of influence**

We can see that the various contexts of the audience affect the utility and interpretation of most aspects of a diagram. Their information needs should drive the goals and content of the diagram. Physical and cultural factors affect the interpretation of the placement, visual encoding, and labeling of the entities in the diagram. Clearly, success depends on allowing contextual considerations to influence all phases of the design process.

## Chapter 4: Perceptual Fundamental Principles

The perceptual fundamental principles take into consideration the function and limits of human perception and cognition. The effects and indications of these considerations are relatively static, and should apply to nearly any diagram, regardless of the audience. These fundamentals are especially relevant in the later, implementation portions of the design process.

### *4.1 Fundamental Principle: Information Availability*

The notion of information availability is based on the premise that the reader should be able to identify and extract knowledge from a diagram with a minimum of difficulty. A diagram with good information availability will help the reader to learn quickly and easily; a diagram with poor information availability will inhibit the reader's efforts to learn.

#### **4.1.1 Knowledge extraction depends on detection and discrimination**

Before a reader can extract knowledge from a diagram, they must first attach meaning to the entities that make up the diagram, and before they can do that they must find and identify the entities. Finding an entity depends on two factors, detection and discrimination. Detection is the ability to identify the entity against the background, and discrimination is the ability to distinguish the entity from the other entities surrounding it (Kosslyn, 1994, p. 269). An entity that cannot be detected and discriminated cannot convey knowledge to the reader (Williams, 2000, pp. 393).

#### **4.1.2 Detection can be addressed with salience strategies**

The ability to detect an entity is a function of the size of the entity and the contrast it has with the background. Increasing the size and contrast of the entity will aid in detection (Williams, 2000, pp. 383). It should be noted that the same factors, size and contrast, contribute to the "salience" of an entity.

Entities with the greatest difference from their background, due to size, color contrast, motion, etc., will be considered most salient by the brain, and, all other things being equal, will be attended to first (Kosslyn, 1994, p. 24). Entities can be made more detectable by increasing their salience.

#### **4.1.3 Discrimination requires contextual consideration**

While detection can be addressed relatively directly by modifying an entity, discrimination can be a more difficult issue to solve, as it requires consideration of the entity's context, rather than just the entity itself. Too many entities presented concurrently can supply too much information to the reader. In these cases, readers will "have trouble discerning individual objects, [as] they cannot tell what to attend to, and they must exert excessive mental effort to understand the graphic." (Horton, 1991, p. 85)

The issue of too much information reducing reader's performance has been described in several contexts. Mayer and Jackson (2005) showed that adding quantitative information to a source document can hinder reader's ability to use the qualitative information in that document. Mayer, Bove, Bryman, Mars, and Tapangco (1996) showed that increasing the amount of text in a summary actually decreased reader performance when compared to readers who were given a shorter, but sufficient, summary. Horton (1991) suggests that "if many different symbols or pieces of information are displayed at the same time, searching for information will be slow, tiring, and error prone (p. 85). Kosslyn (1994) states that "readers use displays to answer questions, and they expect to be told as much information as is necessary in the context in which the [diagram] appears – and no more." He continues to say, "you should not include any more or less information than is needed to make your point" (p. 21). This notion of just enough information can be incorporated into algorithms that are used to draw directed graphs (Gansner, Koutsofios, North, & Vo, 1993).

Another discrimination consideration is the degree to which a particular entity is visually distinct from the other types of entities near it. Preattentive properties are visual properties that can be differentiated from other variations at a glance. Differences in size, shape, line thickness, position, grouping, and color all have the ability to distinguish entities at a preattentive level. However, even with preattentive characteristics, minor differences such as subtle variation in color or small differences in size, may not be sufficient to trigger preattentive differentiation. "If you want people to be able to identify instantaneously some mark on a [diagram] as being of type A, it should be differentiated from all other marks in a preattentive way" (Ware, 2004 p. 151). Generally, adding other, non-target entities to an image will not increase the time it takes to identify preattentively distinct target entities. However, the time it takes to find non-preattentively distinct target entities increases as the number of non-target entities increases. (Ware, 2004, p. 150).

#### **4.1.4 The four components of diagrams**

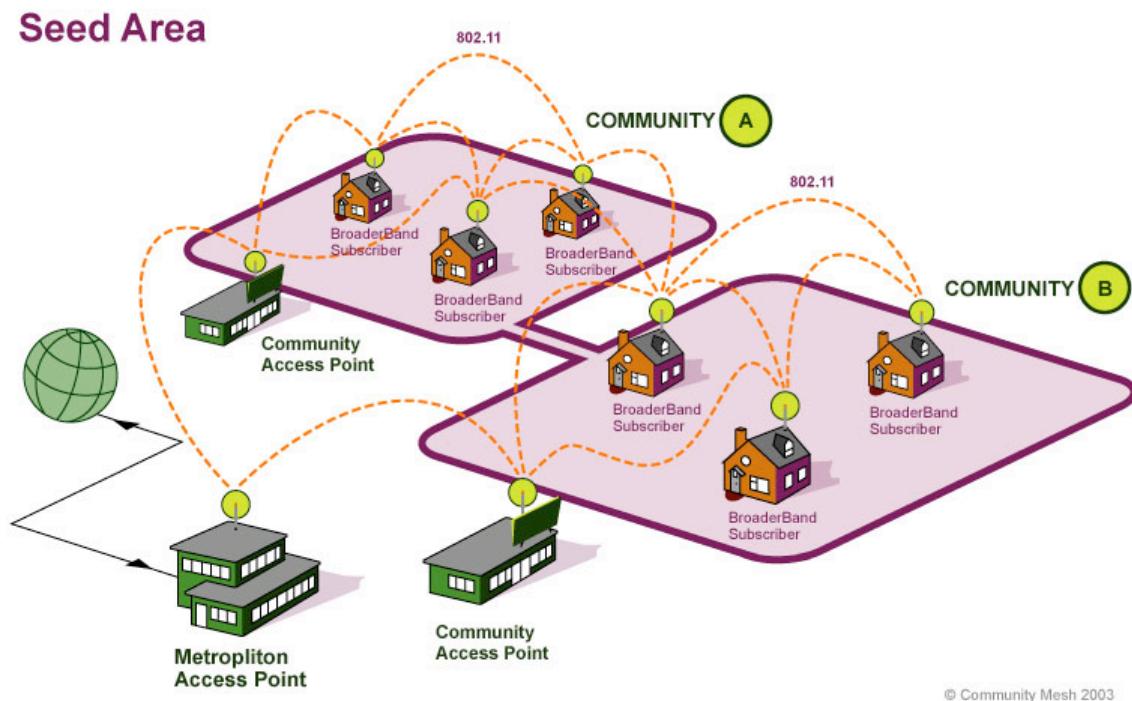
The content of a graphic can be classified into four groups. The relevant, useful content of a graphic is either message or redundancy, and the balance is either decoration or noise (Horton, 1991, p. 27). The message is the information content that is being conveyed to the reader. If part of the message is encoded in multiple ways, such as by shape and by color, it is redundantly encoded. Redundant encoding provides the reader with multiple ways to extract the same knowledge, and has been shown to improve performance (Mayer, 1989).

Visual content that does not contribute to readers' understanding is either decoration or noise. Horton differentiates the two by defining decoration as visual elements that increase the appeal of the image without interfering with the actual message. Noise is anything that does not contribute to the message

or the appeal of the image, and therefore interferes with the message (Horton, 1991, p. 28).

#### 4.1.5 Example: Network diagram with redundancy and decoration

The community network Figure 8 demonstrates good use of redundancy and decoration to enhance a basic diagram and provide a high level of information availability. The goal of the diagram is to show the connection types among different entities.



**Figure 8: Original Community Network (Community Mesh, 2003)**

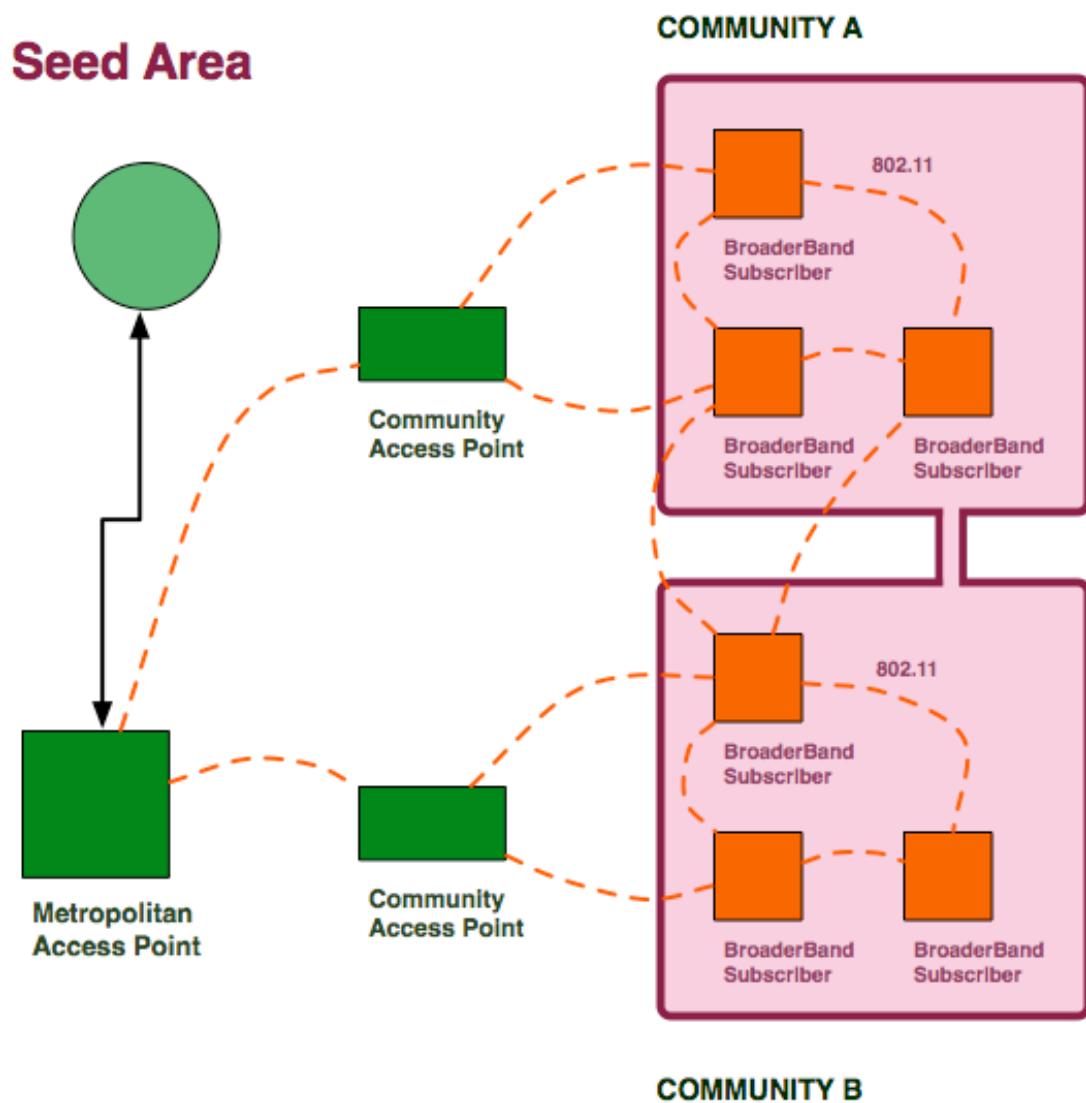
I would evaluate this diagram as having four dimensions of complexity. The first two dimensions are the entities and their hierarchical relationships: the unlabeled globe (presumably the internet), the Metropiliton (sic) Access Point, the Community Access Points, and the BroaderBand Subscribers. The third

dimension of complexity is the encoding of the different connection types: 802.11, and the unlabeled connection from the globe to the Metropliton Access Point. Finally, the subscribers are divided into two connected communities, A and B. The communities are essentially groupings in the hierarchy between the Community Access Points and the Subscribers. More levels of hierarchy would not ordinarily add a dimension of complexity to the diagram. However, in this case the connection between the Communities is relevant, so it can be argued that it counts as an additional dimension of complexity, bringing the total to four.

Beyond the basic encoding of those four dimensions of information, the diagram uses many redundant encodings to convey the message. Each entity is encoded with size, shape, color, text label, and text color. The hierarchy is also encoded with placement and grouping of the entities. The connection types are differentiated by color, solid or dashed line stroke, curved or orthogonal line path, arrows and text labels on the lines, and in the case of the connection between communities, fill style. Any of these alone would be sufficient to differentiate the entities or connections from one another, but taken together they provide the reader with enough visual information to discriminate each entity from its surroundings and uniquely identify it with extreme ease.

Beyond the message and redundancy, the diagram uses a moderate amount of decoration in an attempt increase its appeal. The entities are made to resemble buildings that they represent, and the entire map is given some perspective to enhance the 3D effect. The wireless connections are shown to be terminating at antennas. The aesthetic success of the decoration may be subjective, but I argue that the decoration doesn't substantively inhibit the message of the diagram, and does improve the appeal when compared to a comparable

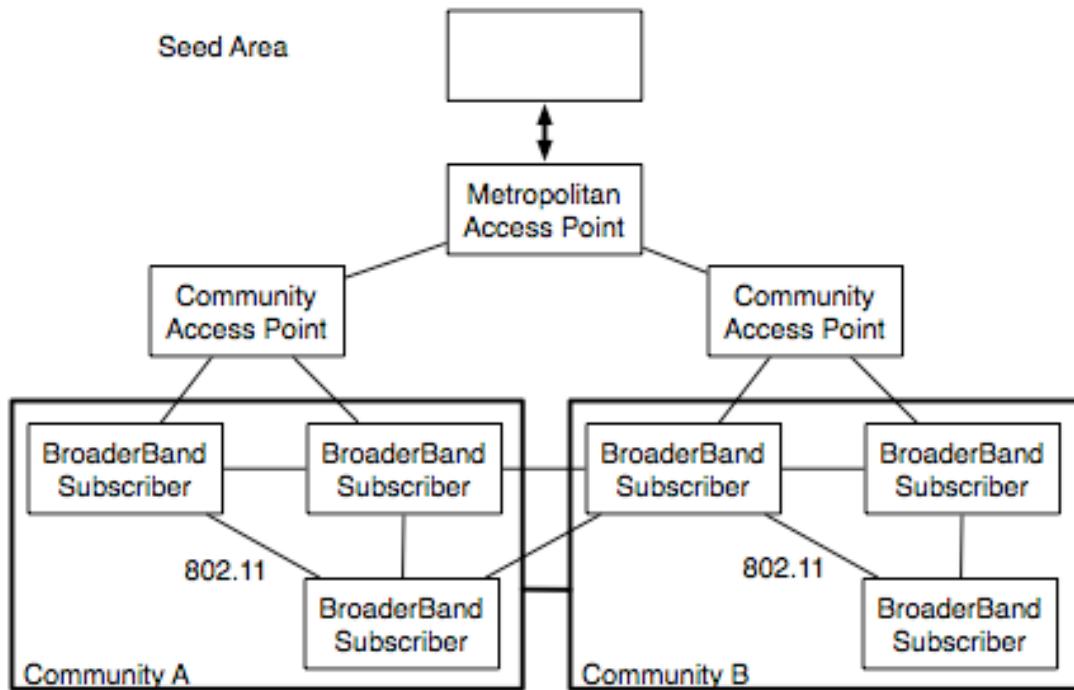
diagram that I created in which the decorative enhancements are removed (Figure 9).



**Figure 9: Community Network With Decorations Removed**

While removing the decoration from the diagram yields a moderate change in information availability, a version of the diagram I designed with minimal

redundancy (Figure 10) becomes much more difficult to extract knowledge from. There are significantly fewer clues to the identity of each entity, making them harder to discriminate from their surroundings. The connection types also suffer from similarity as they are not sufficiently different to trigger preattentive differentiation. Even though the same information exists as in the redundant and decorated versions of the diagram, the overall effect of reduced discrimination in Figure 10 is much lower information availability.



**Figure 10: Community Network with Redundant Encoding Removed**

#### 4.1.6 Example: ICEngineering diagram with useless redundancy and noise

The Institute of Civil Engineering diagram (Figure 11) also attempts to use redundancy and decoration to enhance its message. However, it does not succeed nearly as well.

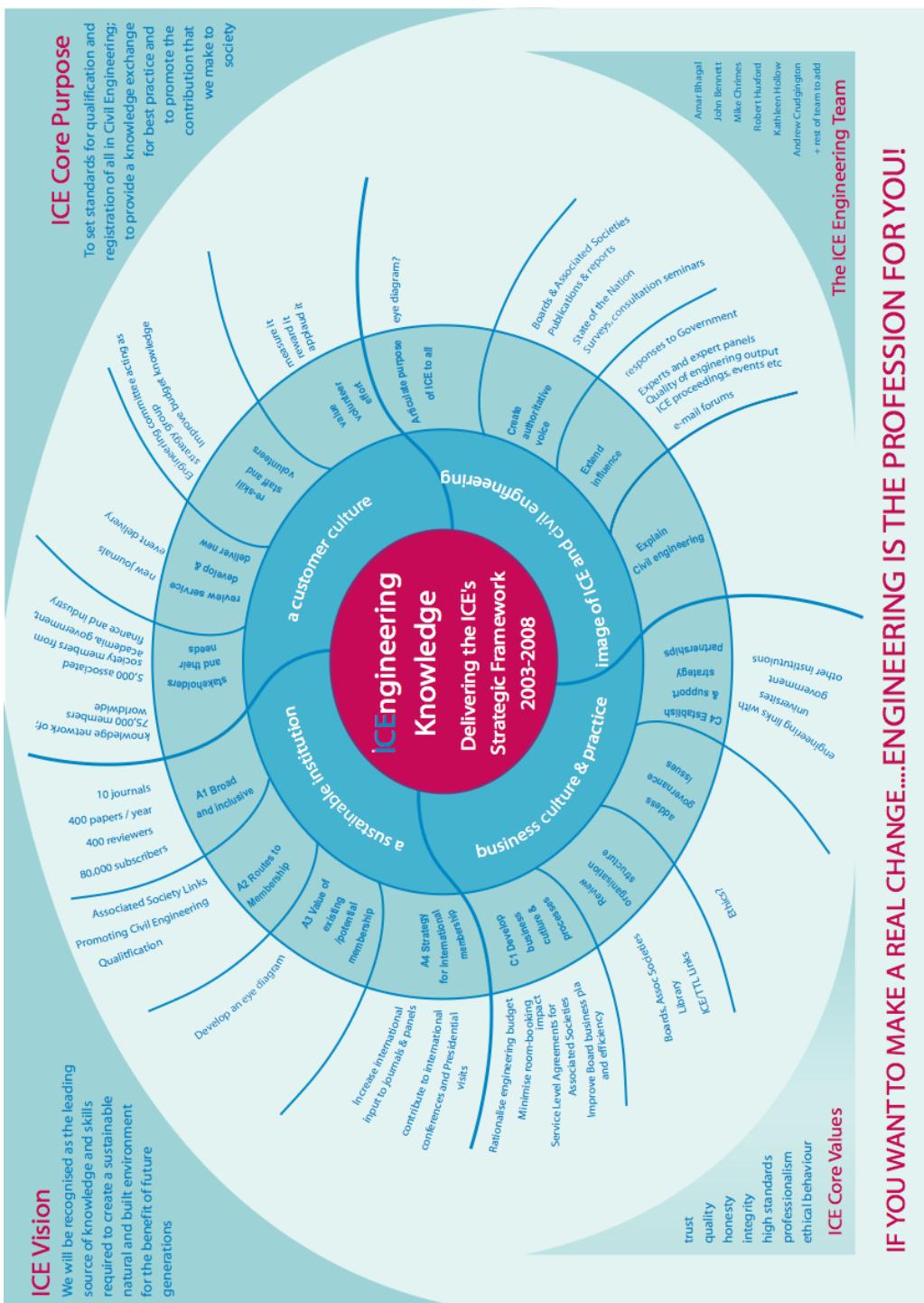


Figure 11: Institute of Civil Engineering Promotional Diagram (Leiper, 2003)

This diagram has only two dimensions of complexity: the hierarchical relationships and the node identities. The text blocks in the corners are outside the hierarchy, but their placement doesn't constitute any additional information beyond their non-relationship with the other nodes.

There is some use of redundancy in the diagram. The shading of each level and dividing concentric blue rings very clearly differentiate the levels of the hierarchy. The levels are further differentiated by the size, weight, polarity, font, and sometimes orientation of the type. The highest level of the hierarchy is extremely differentiated from the next level by the use of red fill color, rather than another shade of blue, and by the orientation and size of the type. However, all of this redundancy does very little to improve the availability of the information, as the spatial positioning conveys the hierarchy rather well.

The diagram suffers from visual treatments that are attempts at decoration but instead end up as noise; that is, attempts were made to make it more appealing, but they instead end up inhibiting the accessibility of the information. The wavy lines that divide each of the four quadrants and the curved lines that divide each node are distracting, and may cause the reader to look for meaning that doesn't exist. Straight lines would have been less distracting. More importantly, the changing orientation among text sections and within individual sections and lines of text makes reading much more difficult, thereby providing a significant impediment to accessing the actual content of the diagram. Finally, the overall effect of a giant eyeball does nothing to enhance or support the message of the diagram, and provides aesthetic appeal that is questionable at best. Therefore, the treatments applied to the diagram in the name of decoration and redundancy largely end up as noise, inhibiting the availability of the information.

#### 4.1.7 Example: Argument maps and effective redundant encoding

Horn's Missile Defense Debate Map (2001), excerpted in Figure 12, tracks the various arguments for and against the central proposition. However the Horn map only shows the local polarity of each argument, whether or not it supports or disputes its immediate parent. Tracking the meaning relative to the central proposition is left as an exercise to the reader.

Three alternate methods are shown in Figure 13, a bicycle commuting argument map that I styled after Horn (2001). The local context for encoding the polarity of the links has been maintained, using culturally neutral colors and shapes. However, much more information has been made available to the reader. Rather than requiring the user to track the global polarity of each argument, this diagram uses culturally meaningful colors to show the polarity of each node relative to the central proposition; green indicates nodes that support the central proposition, and red indicates nodes that oppose it. Three alternatives are shown, using fill color, color and outline style, and color and (culturally significant in the form of "Stop Sign" octagons) outline shape. Each treatment redundantly encodes information that exists, but that is not readily available in the missile defense map: the global polarity of each node.

Encoding each node in such a way improves the information availability of the diagram. It allows the reader to interpret each node more quickly than if they had to track the polarity changes as they progressed along a line of four or five nodes. There are two other significant benefits to this encoding. The first is that the reader can see the relative proportions of globally supporting and opposing arguments at glance (presuming that the sizes of the supporting and opposing nodes are roughly equivalent). The second is that the reader can see the polarity of the final node of each argument thread, thereby giving an indication of the overall current state of the argument with respect to the

central proposition. This quick access to the overall conclusion of the argument is valuable, and impossible on the missile defense map.

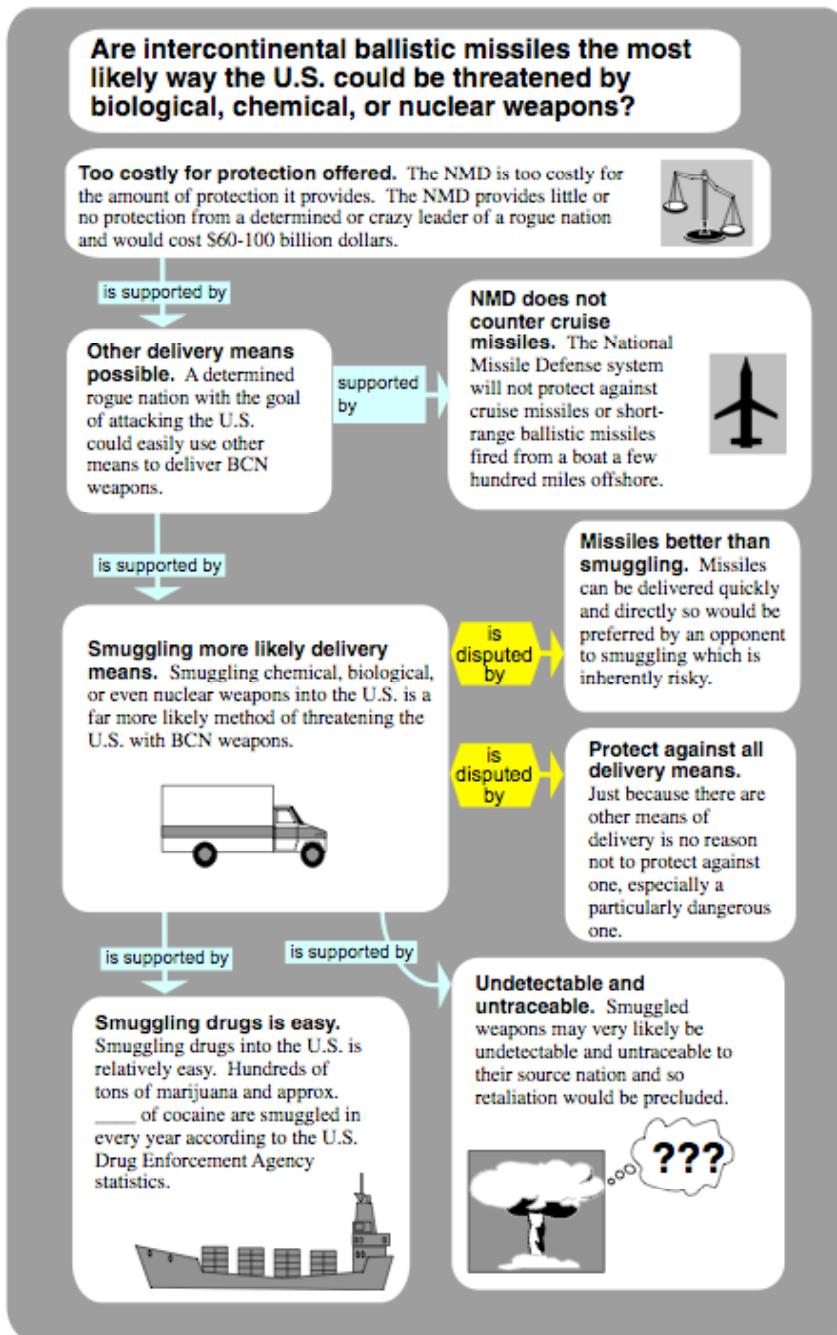


Figure 12: Excerpt from National Missile Defense Debate Map (Horn 2001)

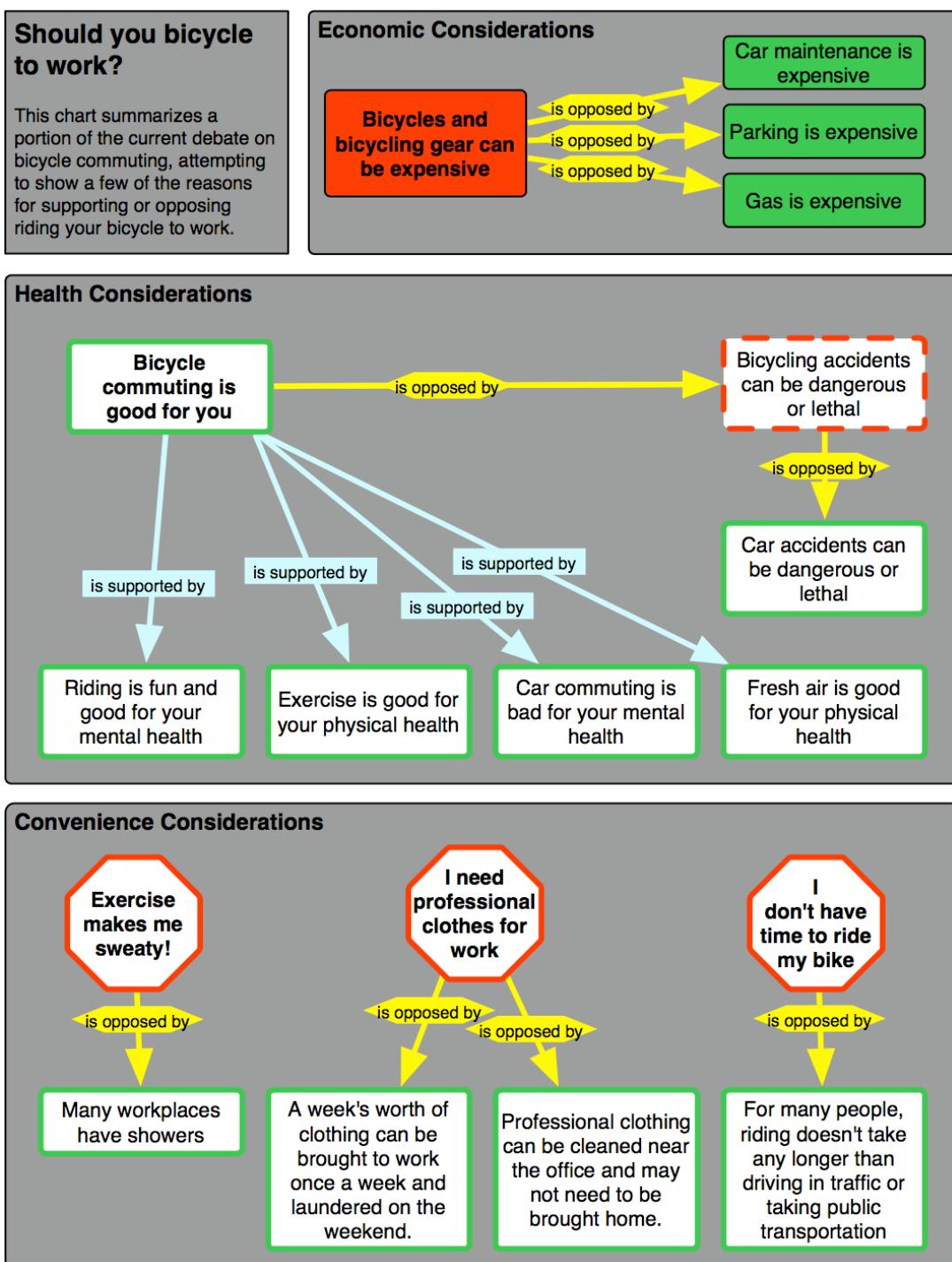


Figure 13: Bicycle Commute Argument Map (styled after Horne 2001)

## ***4.2 Fundamental Principle: Semantic Distance***

### **4.2.1 Spatial aspects differentiate diagrams from text**

According to Winn and Holliday (1982), “both diagrams and charts differ from texts in that the logical or syntactical relationships that exist among the concepts they describe are represented spatially on the page rather than in sentence form” (p. 277). The spatial component not only differentiates diagrams from text, but it is the characteristic that adds value to diagrams and makes them beneficial. Given the importance of spatial placement, it is critical that the diagram designer be aware of how placement will be perceived.

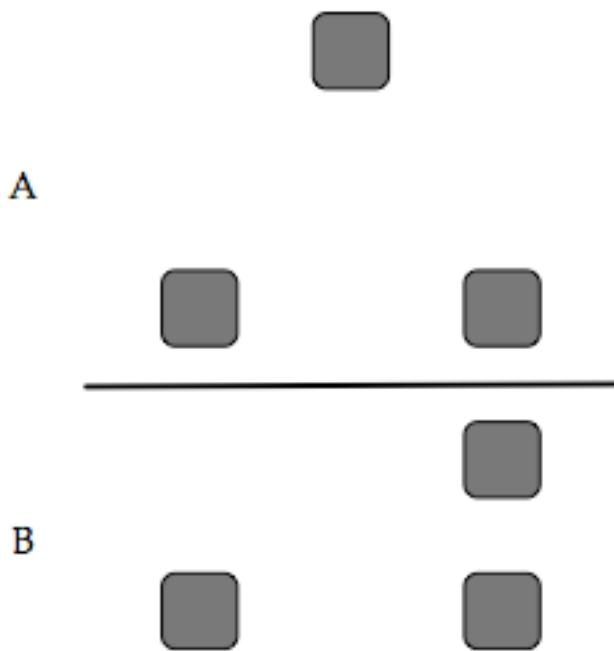
### **4.2.2 Qualitative, spatial relationship**

Placement of the entities (nodes) frequently indicates qualities of the entities, and relationships among entities “using natural correspondences and spatial metaphors” (Tversky, 2001, pp. 89). Entities that are closer to one another on the page will be perceived as conceptually closer than entities located further away from each other, due to the fact that diagrams “express metaphorical proximity in literal spatial terms” (Winn & Holliday, 1982, pp. 279-280). This notion of metaphorical proximity is called semantic distance.

### **4.2.3 Local placement indicates grouping**

Semantic distance has several ramifications for the interpretation, and therefore placement, of entities in a diagram. At the most local scale, entities that are placed relatively close together will be perceived as grouped, chunked, or related. Entities that are placed relatively further apart will not be perceived as part of the same group (Winn, 1991, pp. 221), in accordance with the Gestalt principle of proximity (Moore & Fitz, 1993, pp. 139; Ware, 2004, pp. 189). For example, in Figure 14 the three squares in A do not seem to form a group, whereas the two squares on the right in B do appear to form a group, to the exclusion of the square on the left. Also of note, if there is a line between

entities the reader will perceive them as not belonging to the same group (McNamara, 1986, p. 106-107; Winn, 1991, p. 221). This can be seen in the case of the top two squares in the right column of Figure 14; those squares are as closely spaced as the bottom two, yet don't appear to be grouped, due to the line separating them.



**Figure 14: Grouped Entities**

#### 4.2.4 Absolute placement can be relevant

Absolute placement on the page will also affect the reader's perception of the entity. If the diagram has well defined axes, such as time, depth, or rank, the absolute placement can reveal much about the entity without requiring any visual treatment of the entity itself. Even in the absence of well-defined axes with specific values, placement can reveal information about the relationships among the entities such that those relationships do not need to be explicitly

labeled. These relationships include grouping, order, and interval and ratio between entities (Tversky, 2001, p. 89-96).

#### **4.2.5 Physical placement leads to maps**

At the broadest level, the spatial metaphor implicit in a diagram will cause readers to perceive placement as representation of actual placement in physical space. For this reason, “data about actual positions in space should be presented in the corresponding position in the display” (Kosslyn, 1994, p. 76). Maps are the least abstract implementation of this notion, where orientation, direction, and proximity in the diagram are intended to accurately correspond to reality. As the nature of the diagram becomes more abstract, the exact correspondence between image and reality loosens, and the meaning of placement becomes more metaphorical. This can be useful when the logical relationships of the diagram elements are more important than the literal physical relationships.

#### **4.2.6 Example: The Moscow metro system map with abstracted spatial relationships**

This map is an example of spatial relationships on the page being used to represent primarily logical relationships, namely the sequence of stops along a given route, with only rough correspondence to geographical space. In this case, the readers need to find their metro station in space is secondary to their need to find their station relative to other stations in the region. This is entirely legitimate, insofar as functionally, the reader, as a rider of the metro, has spatial control of their movement only along the single dimension of the metro line. For that reason, a one-dimensional representation of the route, which is to say an ordering, of their choices (stops along the route) is sufficient. Spacing of stops along particular routes is driven by logical grouping where necessary, as in when connecting to other routes. When

logical grouping isn't relevant, the spacing of stops is driven purely by concerns related to layout of the page.

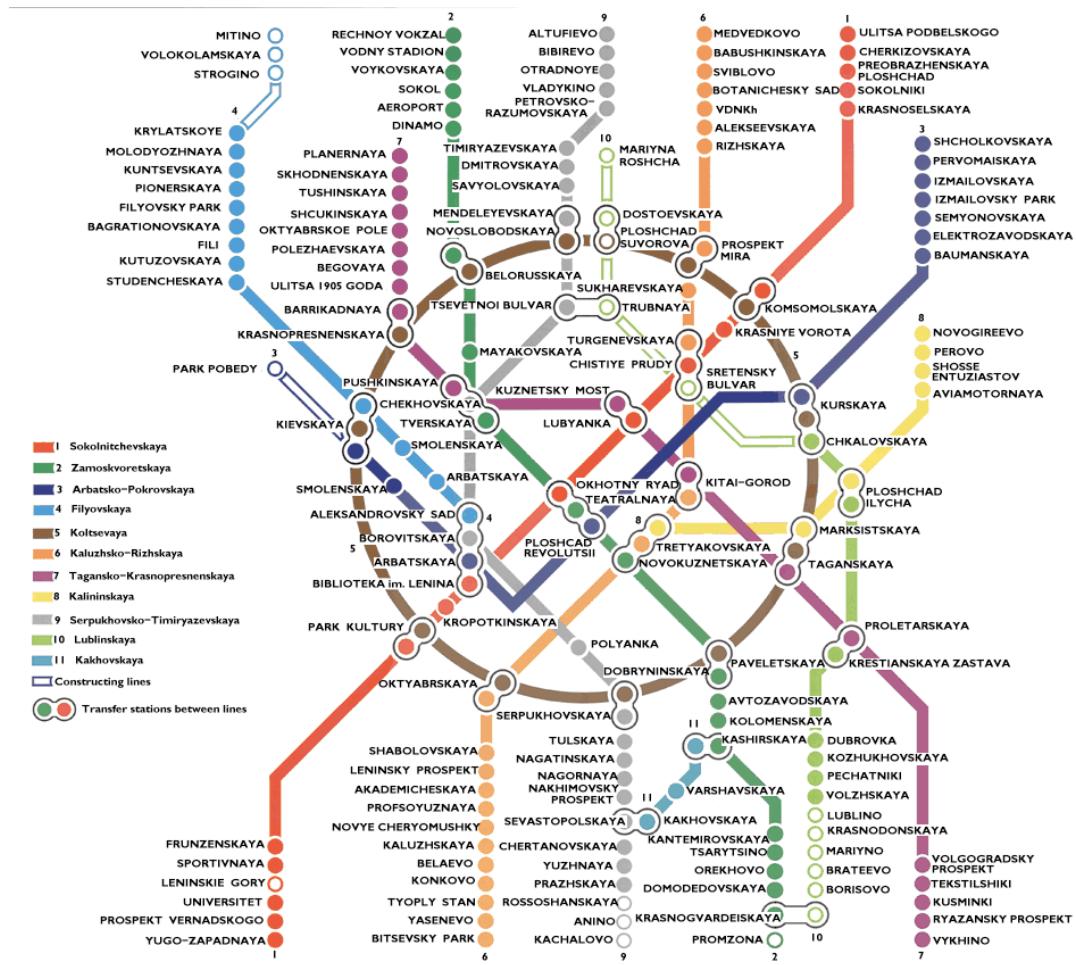


Figure 15: Moscow Metro Map (n. d.)

It should be noted that the map uses line boundaries (the peanut shapes) to indicate grouping of connected stops. Also, the identity of each route is redundantly encoded with color, and by using the Gestalt principle of continuity, which indicates that a smooth and continuous arrangement of entities or links will be perceived as grouped (Ware, 2004, p. 191). Many modern subway systems use this type of abstracted map; this is a particularly

clear example of the genre. The first was drawn in 1933 by Harry Beck for the London Underground (Transport for London, 2006).

### ***4.3 Fundamental Principle: Informative Changes***

#### **4.3.1 Any difference is interpreted as meaningful**

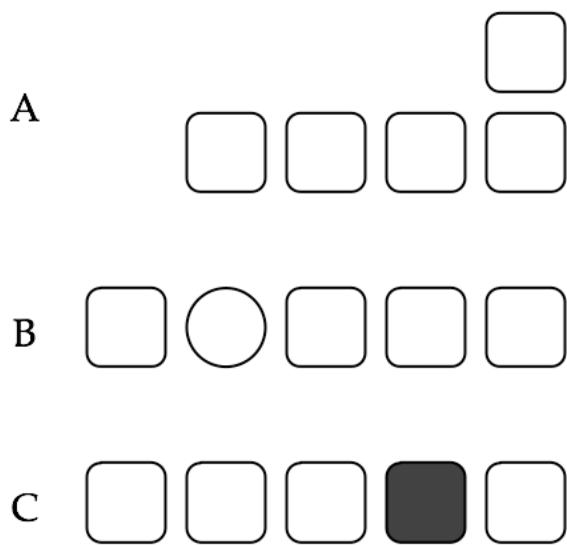
"Readers ... expect any change in a pattern to mean something.... When things stay the same, there is no new information; when something changes, there is-or should be-new information" (Kosslyn, 1994, p. 26). This is the principle of Informative Changes. In the situation of applying a visual style to entities in a diagram, informative changes indicates that in a group of similar objects, one that is dissimilar will be perceived as being different. In this regard, informative changes is complemented by the Gestalt law of similarity, which states that "entities that appear alike in some way, for example, in their style, location, size, orientation, color, and so on, will be grouped together in a viewer's mind. Entities that appear unlike will be separated" (Moore & Fitz, 1993, p. 149)

Informative Changes is a powerful notion that should inform all of our visual design choices. The key is that the human brain is very well suited to noticing patterns. When a pattern is established, violations of that pattern stand out as being different. We recognize these patterns and notice violations, frequently at a pre-attentive (physiological) level. As Kosslyn (1994) says, readers then expect that the violations are meaningful (p. 26).

In Figure 16 the reader can easily identify which of the entities is "different" from the others in each row. Notice that a variation in either placement or style is enough to cause our brain to perceive an entity as different. That's acceptable if the entity is intended to represent something that has a different characteristic, but causes problems if the entities are intended to be the same.

In that situation the reader may be left searching for a difference in meaning that doesn't exist.

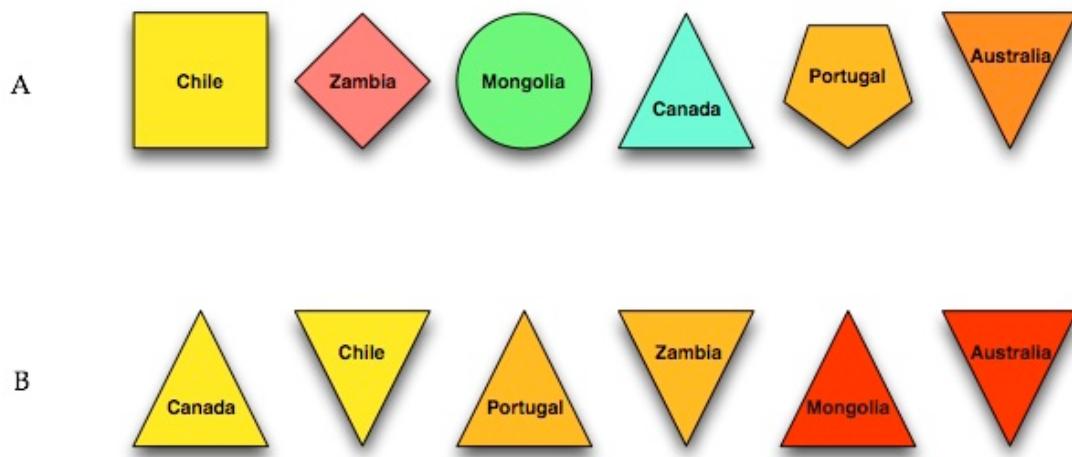
Of special note in this example is the fact that a variation in placement can cause an otherwise identical entity to be perceived as different. This is a useful technique if done intentionally. However, variance in placement is often implemented as a response to limited space on the page. We call this the "real estate problem." It is to be avoided if at all possible.



**Figure 16: Different Entities**

Finally, there are situations where every entity is encoded in a completely different way. For a comparative example, notice the difference that consistency makes between A and B in Figure 17. In B, the reader can make accurate predictions about the entire set of entities, based on their perceptions of the characteristics encoded four different ways in the pattern. The lack of pattern in A makes that type of prediction impossible. While Figure 17 is a trivial example, we can imagine how much more accessible the knowledge embedded in the Wall Street Follies diagram (Figure 5 on page 15) would be if

there were more consistent patterns in the encoding. The nearly complete lack of consistent encoding precludes our ability to learn from a small set of entities and then ascribe meaning to other entities with similar encoding.



**Figure 17: Irregular and Patterned Entities**

#### 4.3.2 Example: BSc Diagram with inconsistent encoding

There are various issues with the BSc diagram (Figure 18) that make it difficult to understand. The major issue is inconsistent, and therefore confusing, choices of encoding style, though there are also some minor problems.

The diagram consists of a matrix of classes offered, and encodes roughly a quarter of them differently from the default, to indicate special considerations for those particular classes. The considerations are whether the class is exchangeable for a language, whether the class is joint study with another department, and whether the class is exchangeable for other study opportunities.

## Programme Structure

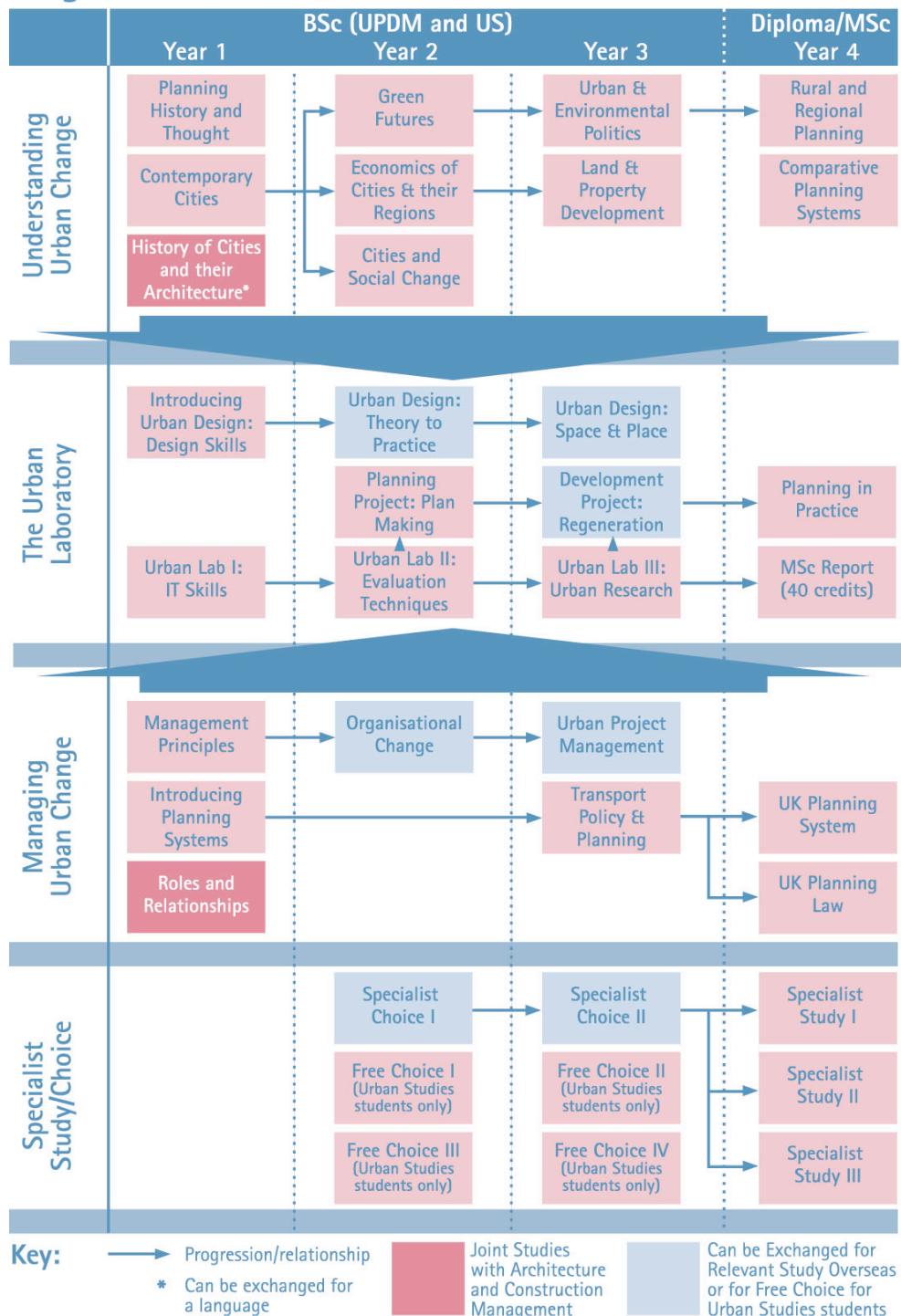


Figure 18: BSc Diagram (Bartlett Planning, n. d.)

The encoding methods chosen to represent these considerations are an asterisk, a different color, and another different color, respectively. The cognitive problem that immediately arises is that exchangeability is encoded by either label or color, while color is used to encode meaning along two different axes, exchangeability and joint study offering. Because of this it is impossible to generalize about what a different color may mean, and there is no predictability which would help the reader learn each variation.

A better version would use a consistent encoding property, color for example, to represent one axis of variation, in this case the exchangeability of the course. Different colors could be used to indicate the different exchanges possible. For the joint studies, an entirely different encoding could be selected. Options include typographic labels, borders on the boxes, shapes of the nodes, or fill pattern, just to name a few.

There are other minor improvements that could be made to the diagram that are unrelated to issues of informative changes. As a pair, blue and pink have cultural meaning that is unrelated to the diagram; a better choice of color scheme would not have meaning that may be misconstrued as significant. Finally, the meaning of the large blue arrows above and below The Urban Laboratory section could be clarified.

In its present form, this diagram has five dimensions of complexity: one for the text that characterizes each course, two more (X and Y placement) for the chronological ordering and the gross groupings (“Understanding Urban Change,” etc.), one for the links indicating progression between specific courses, and one for the color coding of the variations. I will argue that the label encoding (the asterisk) does not count as a sixth dimension of complexity because it is only used once, and isn’t a significant visual component of the diagram.

#### *4.4 Application of the Fundamental Principles*

The five fundamental principles that have been introduced provide a solid foundation to the diagram design process. The next chapter describes the process and begins to show how the fundamental principles can be applied during the process to yield a superior diagram.

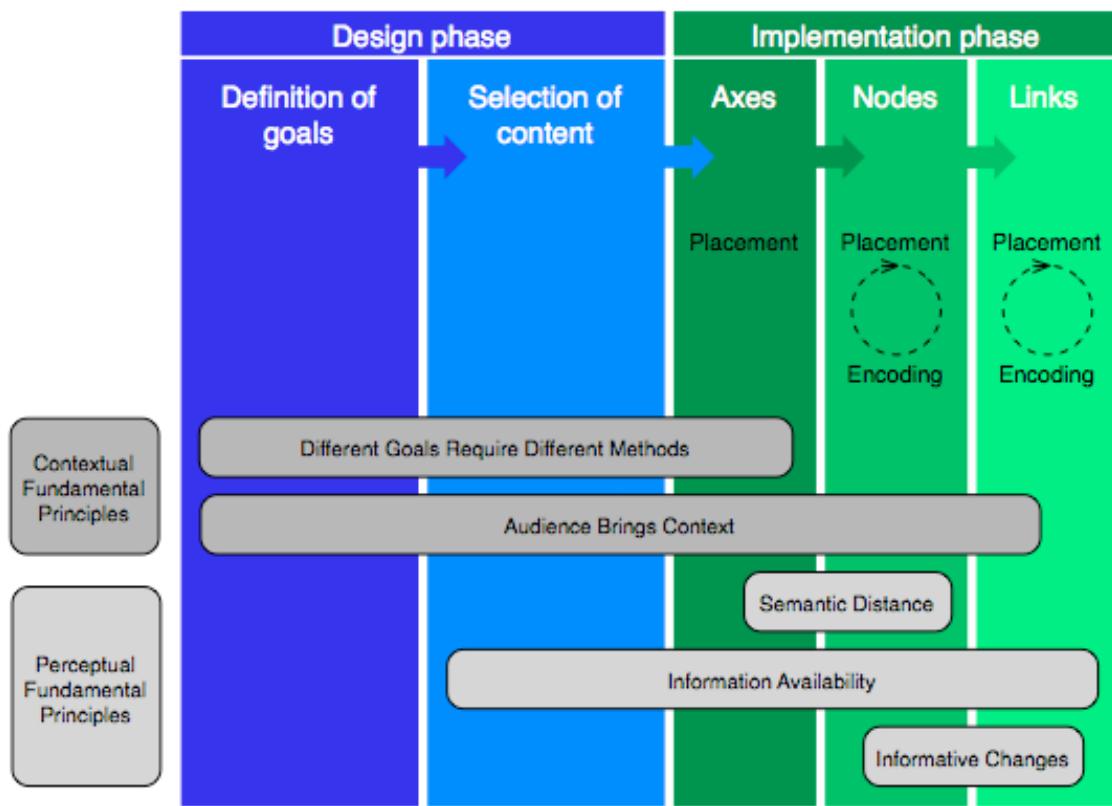
## Chapter 5: The Diagram Design Process

This thesis proposes that complex diagrams can be constructed successfully by making intentional design choices that are informed by the five fundamental principles. This chapter and the next review the design process as it applies to complex diagrams, and discuss how the fundamental principles can inform the choices made in each phase. The goal of these two chapters is to provide a set of instructions that will guide designers as they construct complex diagrams.

### *5.1 Introduction to the diagram design process*

The diagram design process has three major phases: defining your goals, selecting the content, and encoding the content, which involves choosing both placement and visual style of the entities. The first phase, defining your goals, establishes the scope of your diagram, and sets the standard for success. The second phase, selecting the content, is based on and guided by the goals established in the first phase. In the third phase, encoding the content, you will select how to place and visually represent the content in ways that make sense to the reader.

Each of these phases will be informed by various of the fundamental principles, as illustrated in Figure 19. Very broadly, we can say that Different Goals Require Different Methods and Audience Brings Context primarily guide selection of content (including specific axes, nodes, and links) with some help from the principle of Information Availability. Information Availability strongly influences selection and placement of links, and placement of nodes. Semantic Distance also strongly influences placement of nodes. Informative Changes strongly influences placement and visual encoding of nodes and links, with input from Audience Brings Context.



**Figure 19: Design Phases and Corresponding Fundamental Principles**

What follows is an examination of each of these phases and how they are increasingly guided by the fundamental principles. The goals and selection phases will include brief looks at specific implementation suggestions or examples. Chapter 6: presents specific implementation suggestions and examples that includes encoding and placement.

## 5.2 *Introduction to the diagram design family of diagrams*

As each phase is discussed, references will be made to a family of diagrams that reveal the paths from fundamental principles to specific suggestions. Each diagram has a foundation of fundamental principles at the bottom, and builds upward from the fundamental principles to the relevant design principles, considerations, and suggestions. The goal of these diagrams is to provide the

diagram designer with a quick reference, and to show that the suggestions are solidly grounded in the fundamental principles that have been discussed.

The first two diagrams in the diagram design family are Figure 20 and Figure 21 which show the Contextual and Perceptual fundamental principles and the first two levels of derived guidelines. All subsequent diagrams in the family will include and build on content found in these first two.

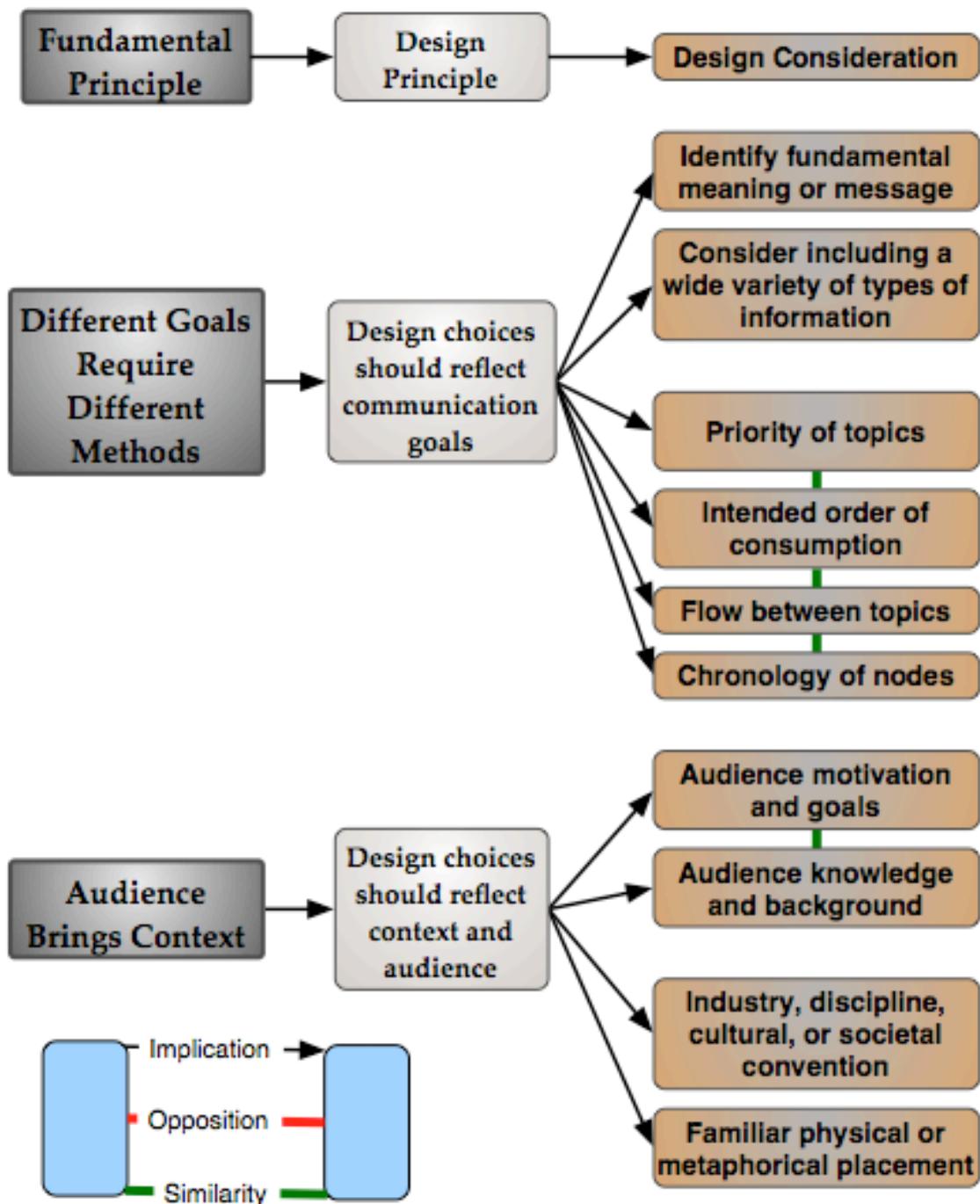


Figure 20: Contextual Fundamentals Diagram

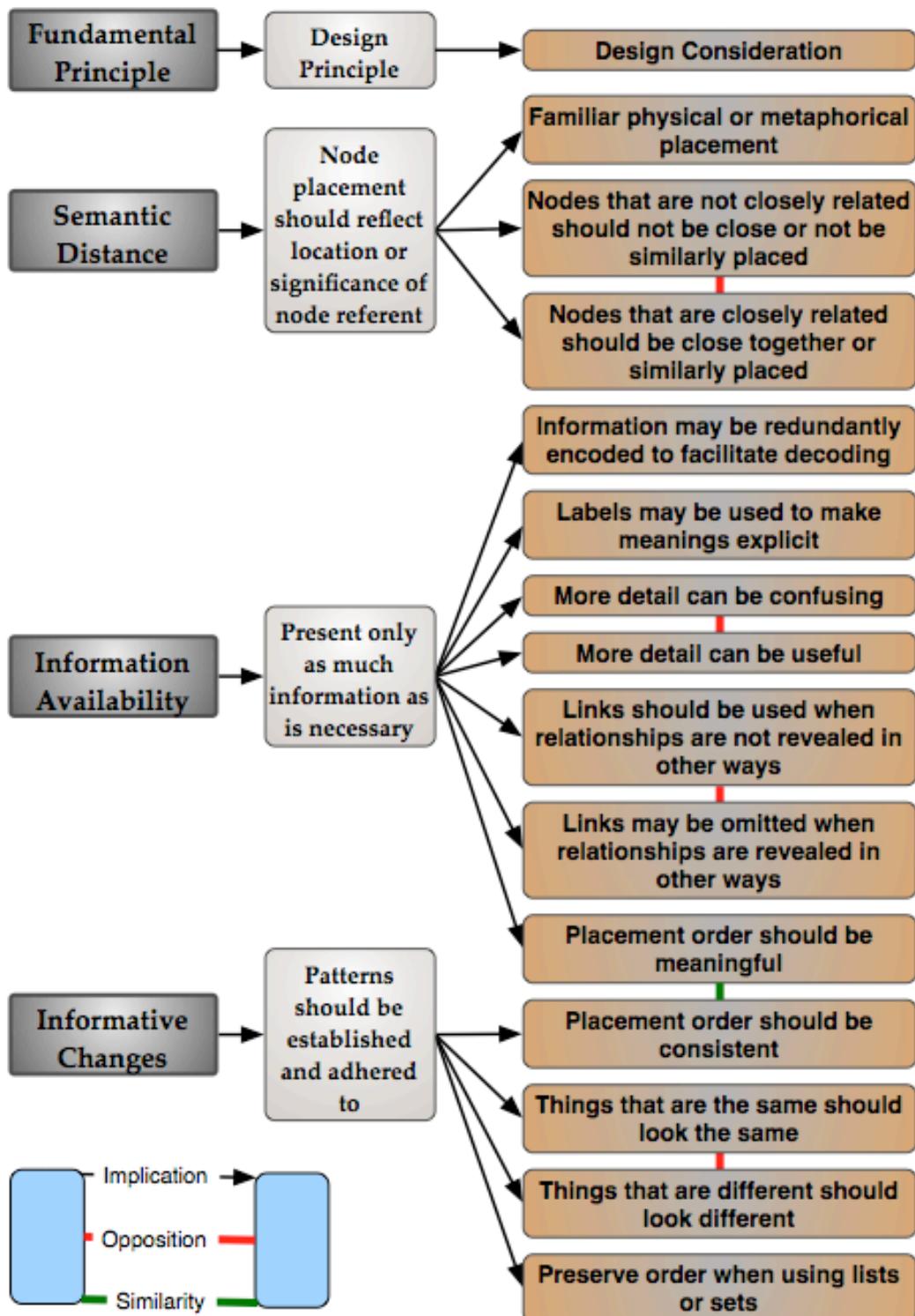


Figure 21: Perceptual Fundamentals Diagram

### ***5.3 Phase One: Definition of Goals***

As discussed in section 3.1, well-defined goals are necessary for any successful design process. Without goals, there is no way to measure the success of the diagram and nothing to guide the design. The exercise of formulating a statement of goals may also be useful in verifying that the entire design team has the same goals in mind. The goals should be stated in terms of the knowledge that can be acquired from the diagram, and should avoid any references to specific content or implementation.

#### **5.3.1 Fundamental principles to consider**

For the goals phase, you should consider the first two fundamental principles, which address the purpose of the diagram, and the needs of the reader who will be extracting knowledge from the diagram. You should have a clear idea of what the diagram is intend to convey, and should keep in mind the fundamental principle Different Goals Require Different Methods.

Communicating this knowledge in a diagram may require a format that is different from other diagrams. Be specific about what is important to convey in this particular instance, and phrase it in terms of the knowledge that is being made available, rather than content that is being included, to get an appropriate goal definition. Consider that relevant knowledge may include a wide variety of components beyond simple nouns, including relationships, actions, changes, implications, intentions, effects, and states of being.

The other half of the goals phase is to consider how the needs of the audience will be met by the diagram. Their biases and needs may be very different from yours. The fundamental principle Audience Brings Context indicates that you must consider the perspective of your audience in order to be successful, and that you will fail if your audience can't satisfy their goals. What the audience needs to accomplish with the diagram and how much information is necessary for them to do it must be considered.

As an example of appropriate goal selection, consider networked clusters of computers running a variety of services and providing a variety of functionality. The goal “show all relationships in these clusters” may be too complicated to be useful to anyone. More specific goals might be “show what functionality each cluster provides,” “show the services running and service dependencies among machines in each cluster,” or “show the physical connections among machines in each cluster and among clusters.” Clearly, these will be very different diagrams with very different focuses and content. As a set, this collection of diagrams may show all possible relationships, but there may not be a single audience that needs to see that much data all at once. Awareness of the message and your audience’s needs will allow you to define viable goals.

## ***5.4 Phase Two: Selection of Content***

The choice of content is entirely dependent on the goals established in phase one. Now that you know what knowledge you want to reveal, you can begin to select the entities and relationships that your message is built from. For this phase, continue to avoid any details of implementation, such as layout, shape, or color. Simply choose the pieces you will build with.

### **5.4.1 General consideration of fundamental principles**

As in the goals phase, remember the fundamental principles of Different Goals Require Different Methods, and Audience Brings Context (henceforth DGRDM and ABC), so that you select entities that are necessary to your message and to your audience. However, you should now also be cognizant of the Information Availability (IA) implications of your choices. Each entity that is included must contribute to the goals of the diagram. Extraneous content will obscure the message and complicate the extraction of knowledge.

When considering what content to include, DGRDM suggests considering the sort of nouns, verbs, and relationships you may want to include and represent. Think about relationships that are sometimes implied or understood, but not necessarily represented, especially those that are directly related to your goals. Keep your goals in mind, and select elements that are directly in service to those goals.

ABC reminds you to consider the audience's bias as you select your content. Don't forget the most basic components of communicating with your audience, including their language and jargon, professional and cultural bias, and level of training or background in the topic. Continue to keep their goals in mind and make sure that the content you are selecting is actually going to meet their needs.

Consider how much time your audience has to read and absorb the information you are presenting, and how much detail will be useful to them. If you are at all unsure about whether to include some content, remember that you are aiming for a high level of Information Availability. The key components should be present but should not be obfuscated by too many low-priority elements. If elements seem to have conflicts in priority, you may have defined your goals too broadly.

### 5.4.2 Diagram Components

There are three types of components that comprise a diagram: axes, nodes, and links. The axes of your diagram define the relationships implied by the layout of your nodes, giving meaning to their placement. The nodes are your basic building blocks, and will likely represent nouns, system states, groups, phases, actions, and discrete chunks of content. The links are the glue of your diagram; they make the relationships among the nodes explicit. Links may

represent flow, sequence, causality, influence, hierarchy, and verbs or actions, among other things.

#### **5.4.3 Considerations for axes**

Appropriately selected axes can convey a huge amount of information in a very unobtrusive manner. Consequently, well-defined axes should be used if at all possible. Failure to convey meaning by using the axes can result in a directionless diagram, such as Figure 22. As shown in Figure 23, axes might indicate chronology, flow, or hierarchy, among other things. Consider how they will guide or inform the reader. Keep in mind typical axes for your context, and the native range of values to be expected.

#### **5.4.4 Considerations for nodes**

Figure 24 shows that there are a vast number of possibilities for the meaning of nodes. In addition to the usual nouns, people, computers, etc., nodes may encompass hierarchical, chronological, or phased groups. They may represent stages in a process (grinding, sorting, etc.), or motivations (increase yield). In some cases, nodes may be preferable to links if more text or other encoding is desired to describe that entity.

#### **5.4.5 Considerations for links**

Links may show any manner of relationship between nodes, including ownership or hierarchy, causality or other influence, support, opposition, affinity, or parallels, as shown in Figure 25. Links may be used to guide the reader along desired or interesting paths, or may reveal relationships that are otherwise not revealed by placement or other encoding. Conversely, if the placement or other encoding of the nodes reveals relationships such as order, hierarchical level, or chronology, links may not be necessary, and may be left out, if their inclusion would add more noise than message. Note, for example,

the lack of links indicating chronology in Figure 7, the Harvey speech diagram.

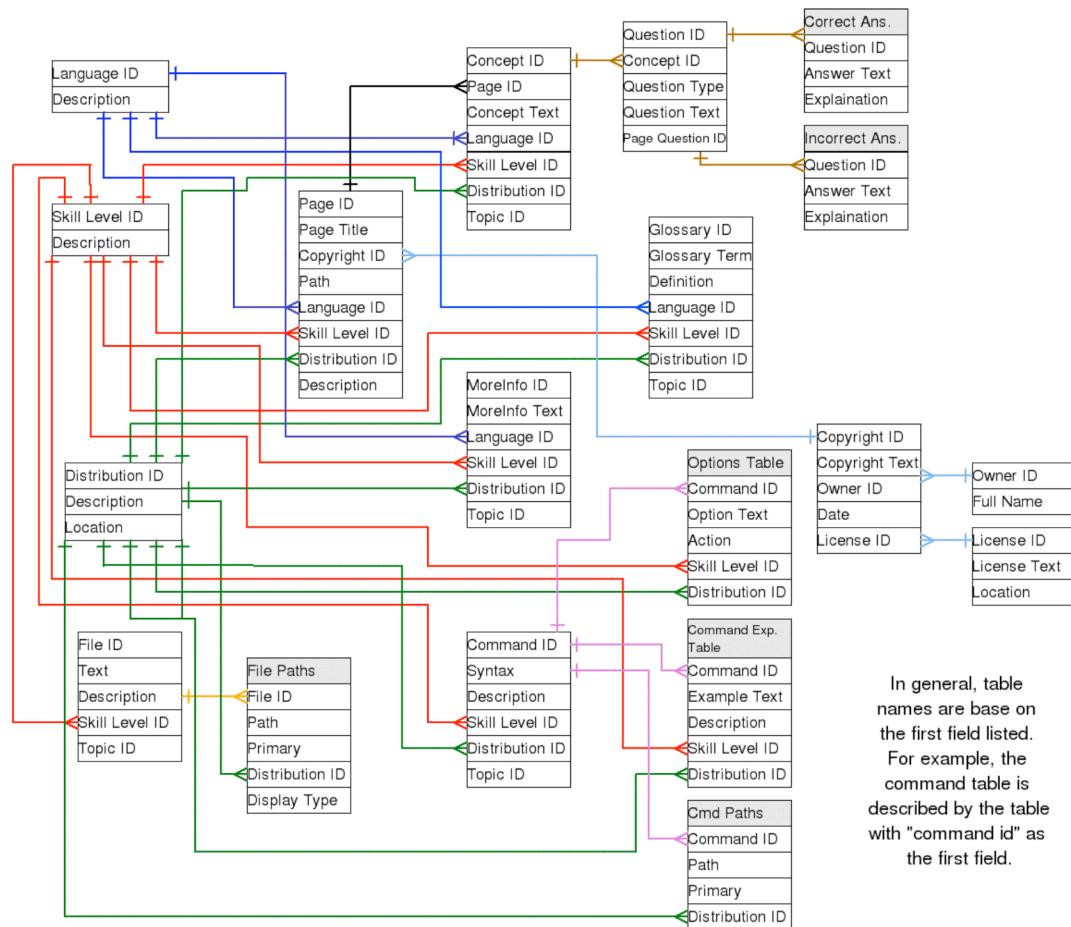


Figure 22: Entity Relationship Diagram, without useful axes (Linkbat, n. d.)

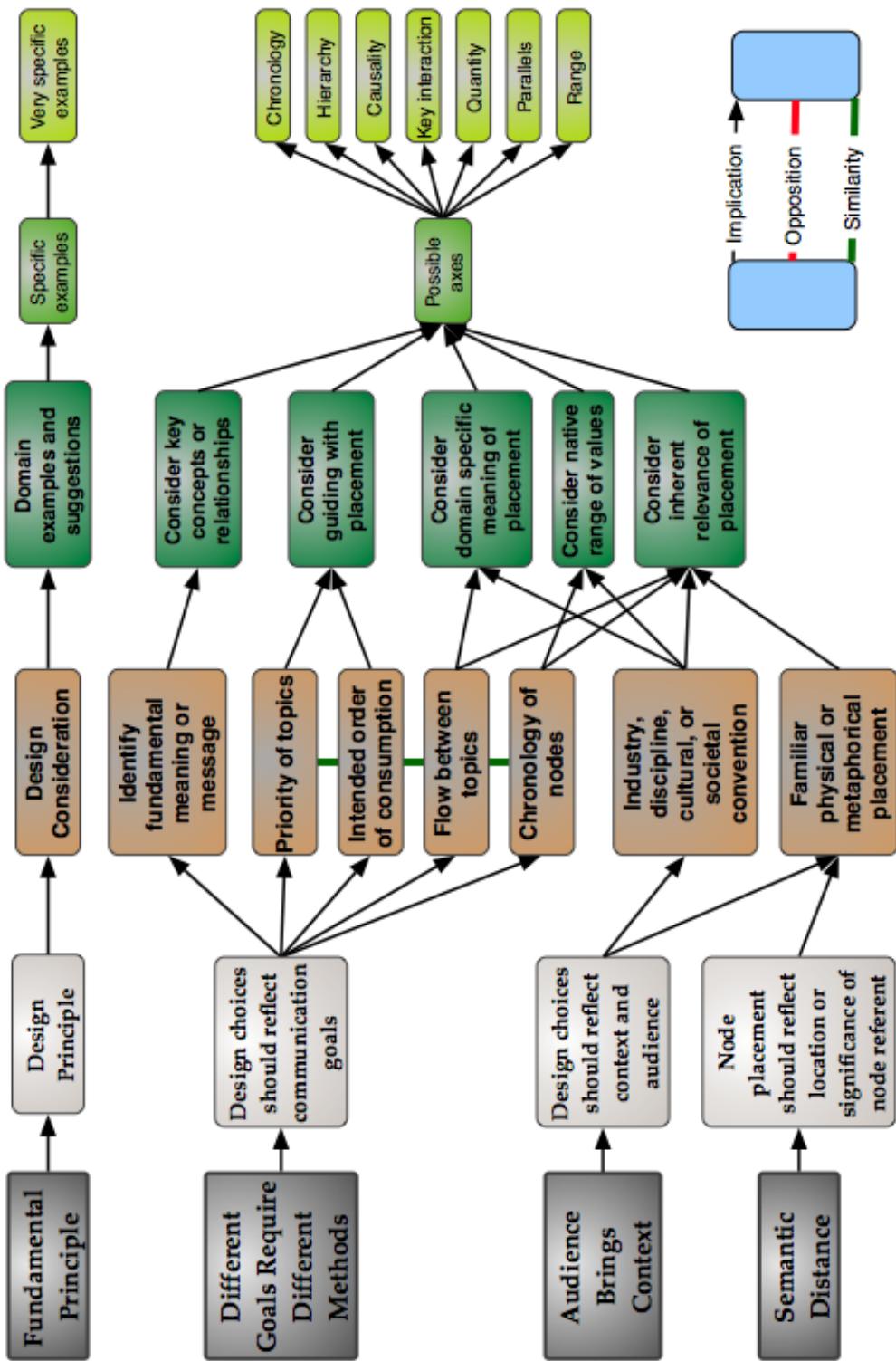


Figure 23: Axis Selection

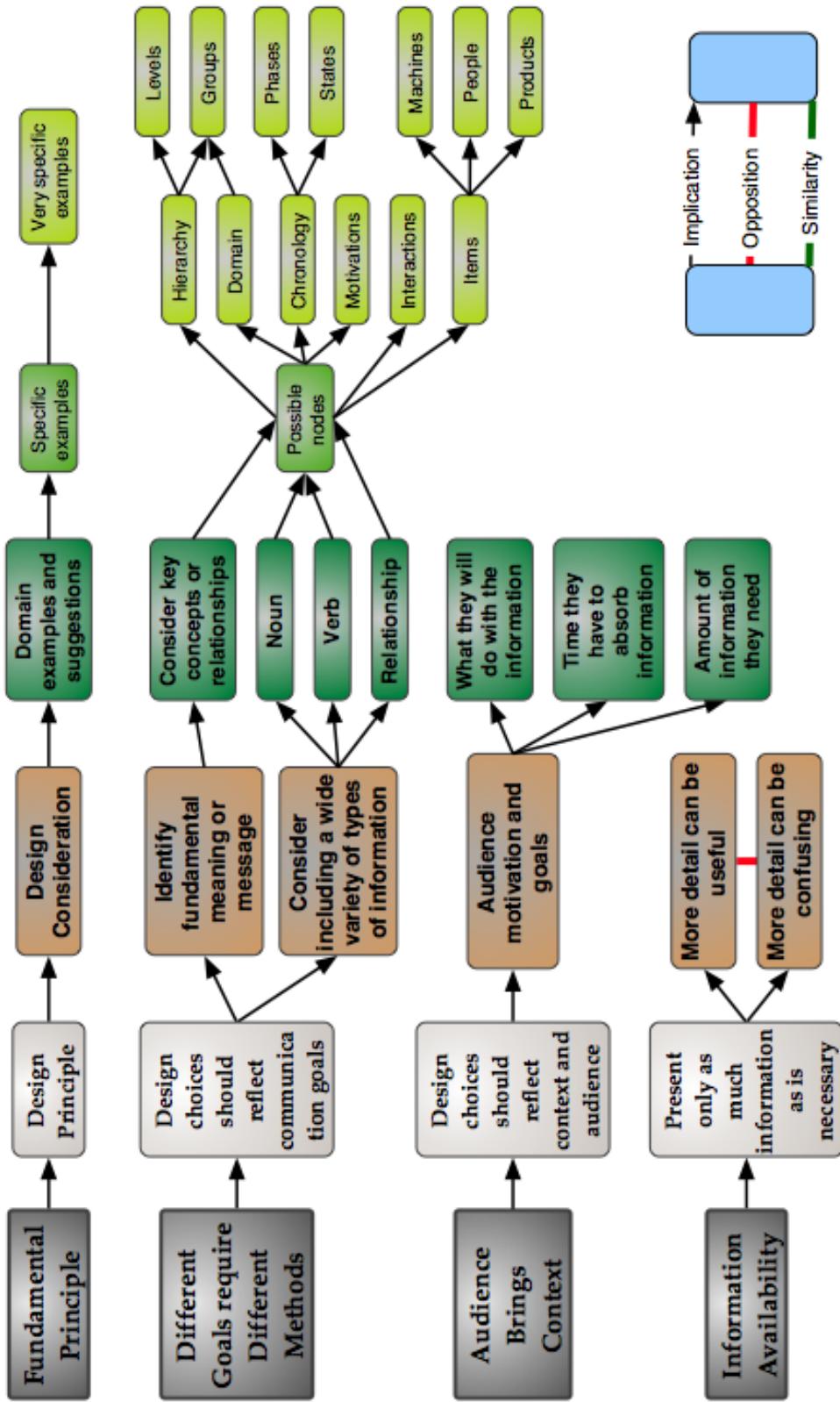


Figure 24: Node Selection

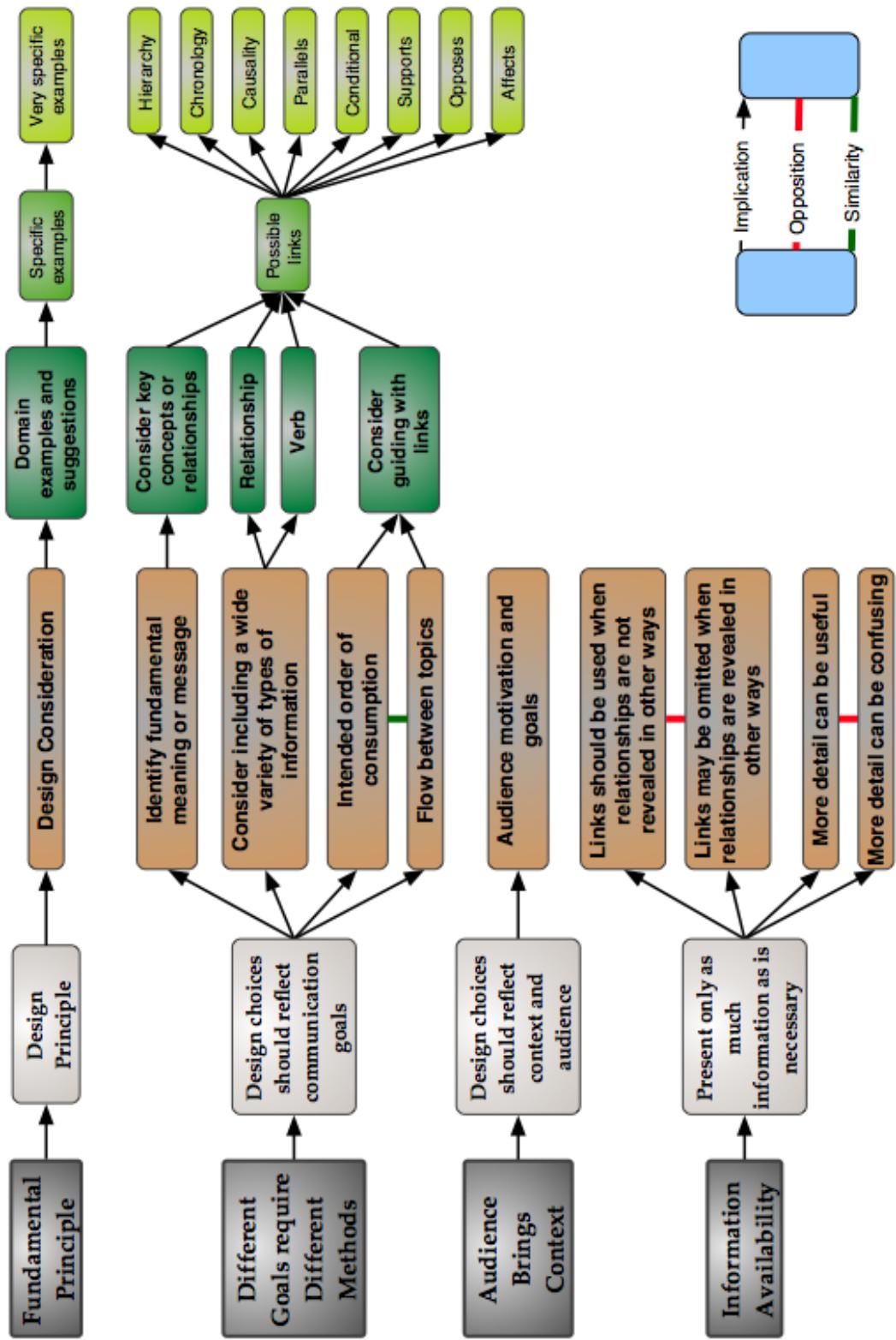


Figure 25: Link Selection

## Chapter 6: Guidelines for Encoding Content

Once you select your components you can begin the final phase. In the encoding phase you will choose appropriate placement and visual representation of your content. This includes the definition of axes, the placement of the elements, the look of each type of element, and the creation of links between the elements. In addition to the fundamental principles used in defining your goals and selecting content, the process of encoding your content will be significantly guided by the fundamental principles of Semantic Distance and Informative Changes. These relationships are represented in Figure 19 on page 50. This chapter examines the choices available when selecting encodings.

### *6.1 Choosing Encoding Properties*

The process of choosing a good class of visual properties (i. e., shape, color, etc.) to represent a class of characteristics will be given special attention here, as making appropriate choices can be difficult, and making changes to entire classes of encoding can be particularly disruptive to existing design choices.

#### **6.1.1 Matching characteristics with properties**

The process of selecting visual properties to encode your characteristics can be tricky. There may be issues with dependencies, where selection of one encoding style or method may have significant influence on subsequent encoding choices. For example, use of color to encode one characteristic may preclude use of color to encode other characteristics. It is likely that revisions and iterations of the encoding choices will be necessary, as new information is incorporated.

Thought should be put into selecting specific visual properties to represent each characteristic. Ideally, before any choices are made, each characteristic to

be represented should be listed with some information about the number and type of variations of that characteristic.

Some characteristics have very few variations (Northern or Southern hemisphere), while others have many (wine grape varietes). The variations of some characteristics are inherently ordered (hierarchy, chronology), while others have no inherent order (flavor). Knowing the various representation needs of each characteristic will guide your selection of an encoding property to represent that characteristic.

Encoding properties have similar classifications. There are many variations of shape, type style, texture, and color, though most are not easily ordered. The size, thickness and weight of lines, shapes, and type are inherently ordered, though there are practical limits to the number of variations of these that can be displayed and (easily) decoded. Placement can potentially display as many ordered values as there are entities placed.

Once the relevant characteristics have been identified and quantified, they may be paired with appropriate visual properties. Once that level has been reached, contextual considerations, such as culture or industry standard, should be consulted for specific pairings (red for stop, green for go).

If there are extra properties that are not being used, they may be employed to redundantly encode meaning. For example, see the redundant use of color and vertical placement of the nodes in the Harvey Speech diagram (Figure 7 on page 22), or the redundant use of color, shape, and size in the Community Network (Figure 8 on page 30).

### 6.1.2 Other sources to consult when choosing encoding properties

Ware (2004) discusses a few recommended encoding styles for nodes and links, based on perceptual properties (p. 213-215). Readers interested in a rigorous examination of the process of choosing encodings should see Bertin (1983), starting with Part One: Section I.

## 6.2 *Axis Placement and Encoding*

### 6.2.1 Basic axis encoding

For axes, there is very little difference between placement and encoding. Once an axis has been selected (e.g. time, rank, etc.), the only choices left are orientation (vertical, horizontal, other) and direction (e.g. newest on top or newest on bottom). Figure 26 shows many suggestions and considerations for selecting an axis encoding. Axis encoding will primarily be guided by Audience Brings Context and Semantic Distance. It should be noted that Tversky, Kugelmass, and Winter (1991) report very strong correlation between test subject's choice of direction of increasing value in diagrams and the direction of their written language. English speakers, used to left-to-right language, also select left-to-right as the direction of increase in diagrams. All test subjects showed a preference for bottom-to-top to indicate increase on the vertical axis (539-540).

Other than the usual vertical and horizontal choices, which are assumed as the default for most of this document, there are a few other axis options that may be worth considering.

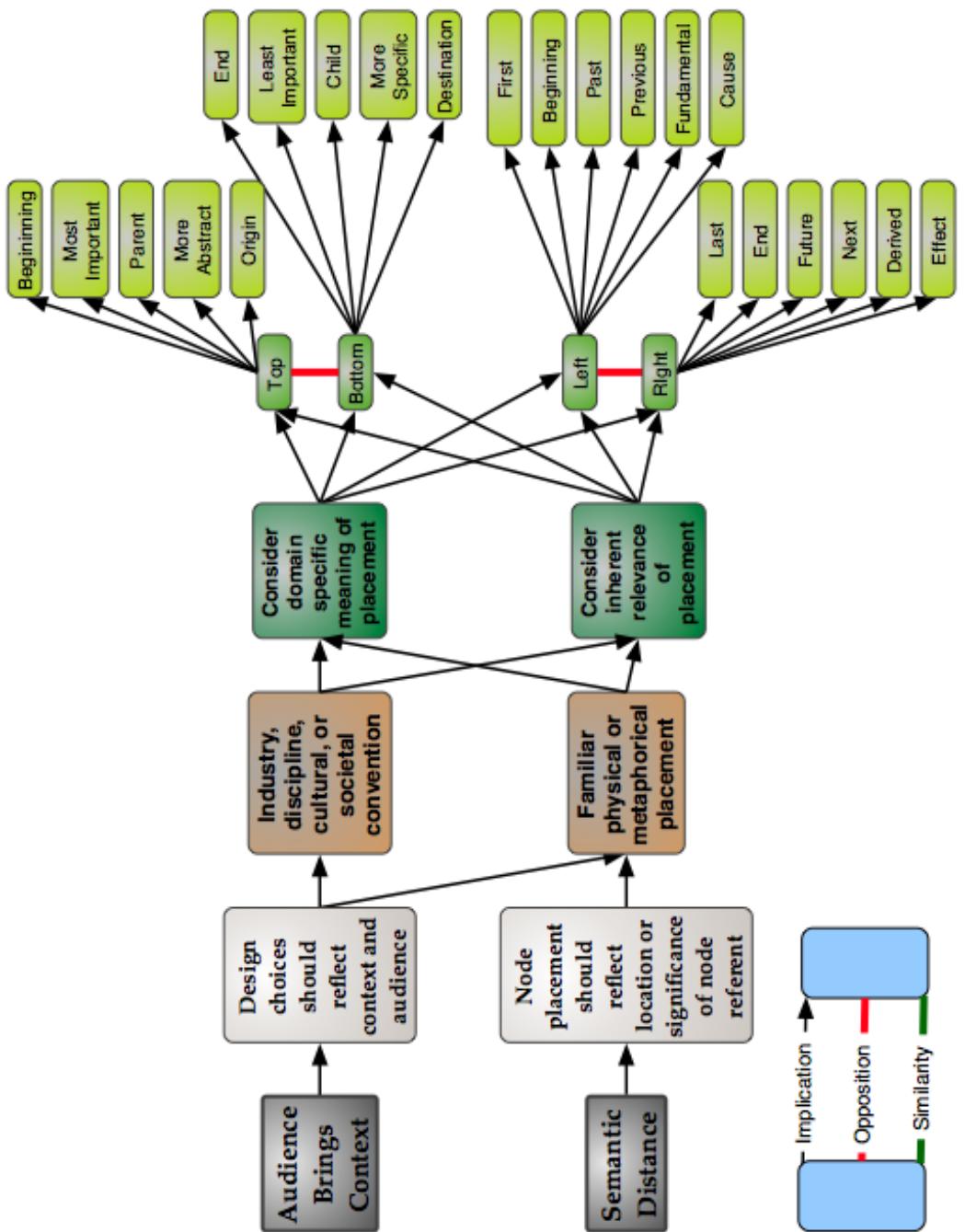
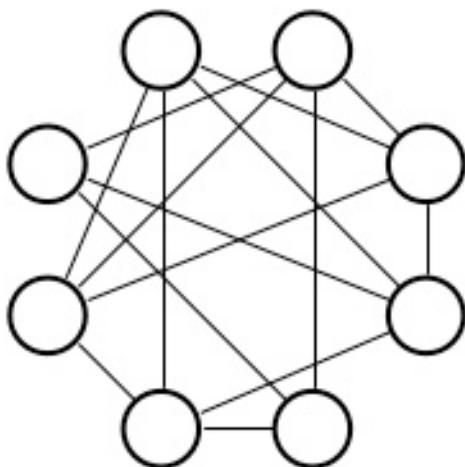


Figure 26: Axis Placement and Encoding

### 6.2.2 Circular layout

Circular layouts are particularly advantageous in a few circumstances. First and foremost, systems that move in cycles may benefit from circular layouts that resemble the key interaction of the systems. It will also accommodate the connections between various phases of the cycle more easily than a linear layout.

Systems with a large number of many-to-many connections may benefit from a circular layout, where each node has a clear path to every other node, as in Figure 27. This will yield a high number of intersecting links, which might normally pose a problem, but shouldn't inhibit clarity in this format.



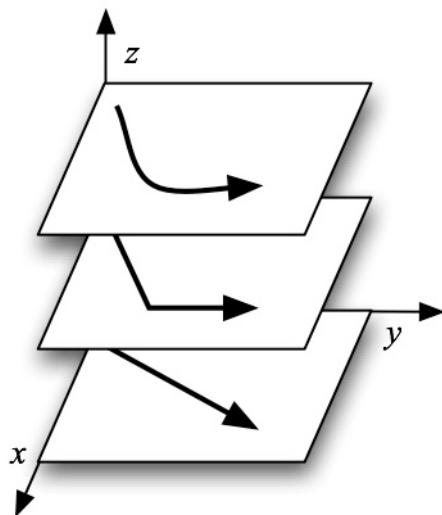
**Figure 27: Many-to-many circular layout**

Finally, hierarchical systems that would be prohibitively wide may benefit from circular encoding. This approach is used in Figure 11: ICEngineering on page 34. That specific example isn't particularly vast, but hierarchies on much more massive scales, such as the classification of every organism in the animal kingdom, benefit from non-linear arrangement.

### 6.2.3 Use of the z axis

As with circular layouts, there are a few situations that will benefit from using a third spatial dimension to layout elements in a diagram. It can be used as a third quantitative axis to display magnitude of objects that are located on an x-y plane, for example.

Vertical space can also be used to represent layers or variations that are literally or metaphorically stacked. Brinton (1917) suggests displaying many floors of a factory in many stacked layers of a single diagram that represents routing among those floors (p. 19). Figure 28 shows an example of three different layers stacked for comparison purposes.



**Figure 28: Layers stacked in the z direction**

Finally, the z axis can be used for decorative purposes, to enable 3-D representations of diagram elements, as in Figure 8 on page 30.

### ***6.3 Node Placement and Encoding***

Nodes have the richest selection of encoding properties available, and consequently may present the most challenging encoding experience. The shape of each node may be simple and abstract or more detailed and representational. Line style and weight, fill style, color, and font size, weight, and style are some of the properties that can be used to great effect. See Figure 8: Community Network on page 30 for an example of the use of color, size, shape, and type styling to encode nodes.

When encoding nodes, significant considerations come from Informative Changes, as shown in Figure 29. Readers expect any change in a pattern to mean something, so patterns should be established and adhered to. Readers should be able to perceive the patterns and extrapolate meaning to the entire diagram based on the patterns that they perceive. Order of lists and placements should be consistent. Single properties, such as color, should be used to encode variations single characteristics. Confusion results when single properties are used to encode multiple characteristics, as in Figure 18: BSc Diagram, on page 46.

Placement should be largely guided by Semantic Distance. Spacing, proximity, and grouping can all convey meaning about node relationships. Nodes may touch, overlap, or enclose other nodes to represent different degrees or styles of relationship. See Figure 6: Book Hierarchy, on page 20 for an example of meaningful node contact and nesting.

As with all design choices, Audience Brings Context suggests the context of the diagram and the reader should inform choice of shape, color, order, and any other properties that have conventional meaning in the context or to the audience of the diagram.

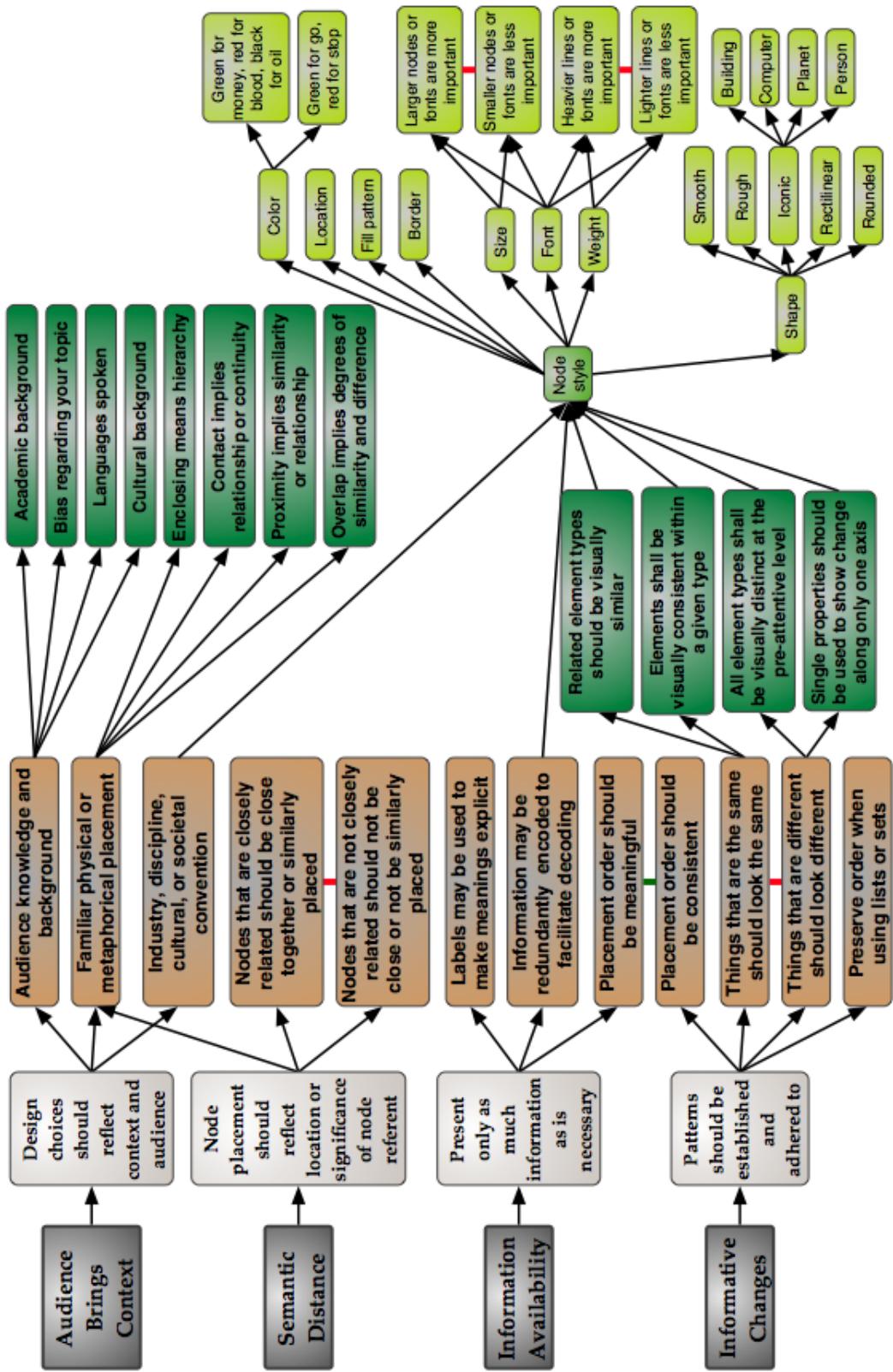


Figure 29: Node Placement and Encoding

#### ***6.4 Link Placement and Encoding***

Links reveal the relationships among nodes that may or may not be revealed by placement of the nodes relative to each other and relative to the axes. Links should be used to highlight the most interesting relationships, and may be omitted for less relevant relationships, or relationships that are otherwise represented, as in Figure 7: Harvey Speech diagram on page 22.

If space allows or priority dictates, links may be labeled directly. If there are space constraints, or few types to differentiate, a key may be used, as indicated by Information Availability in Figure 30.

As with nodes, Informative Changes and Audience Brings Context should dominate the consideration of the visual style of links. As with nodes, consistent use of encoding styles are critical to success. As usual, the counterexample is Figure 5: Wall Street Follies on page 15.

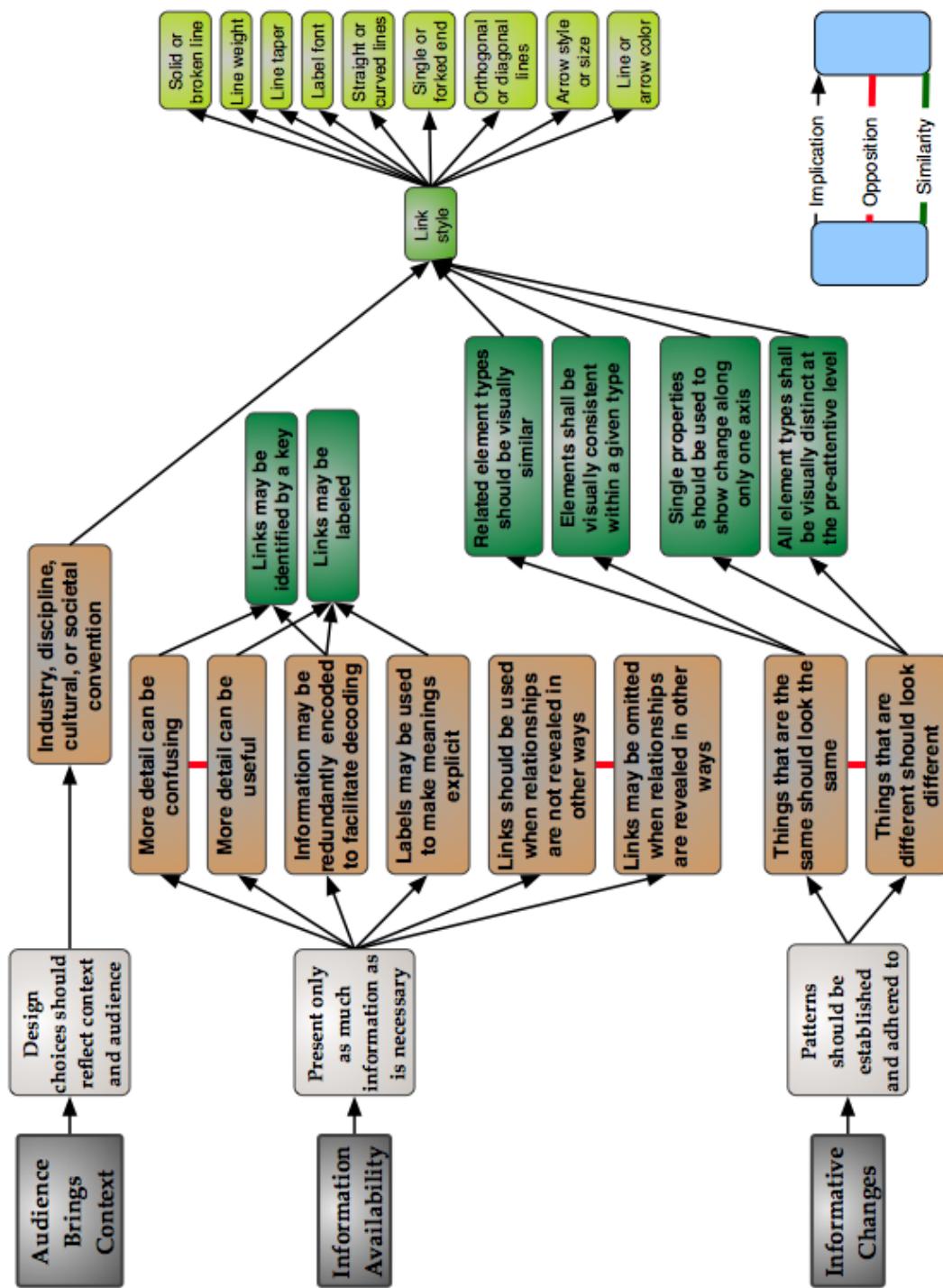


Figure 30: Link Placement and Encoding

## 6.5 *Common encoding errors*

The most frequent problems that I have encountered with poor diagrams fall into two main categories: not using a sufficient number of encoding methods, even when they are available, and inconsistencies in encoding. This section will provide examples of each of those problems.

### 6.5.1 Failure to use all of the graphical tools available

When designing a diagram, authors frequently don't take advantage of the various encoding properties that are available. This leads to insufficiently differentiated entities, which forces readers to work harder to extract knowledge.

Failing to capitalize on the potential of the axes, and therefore placement of nodes, to convey meaning, is a frequent oversight. Even non-quantitative axes can be useful for ordering content and revealing knowledge, as shown in Figure 7: Harvey Speech, on page 22. Failure to use the axes results in arbitrary placement, as in Figure 22: Entity Relationship Diagram on page 58. This, in turn can lead to many crossed links which further impedes knowledge extraction.

Another example of failure to use the properties that are available is shown in Figure 12: Missile Defense Debate on page 37. Adding encoding to the existing entities makes their meaning becomes more accessible to the reader, as is demonstrated in section 4.1.7.

Finally, arbitrary use of encoding properties is little better than failure to use them at all. Figure 5: Wall Street Follies, on page 15, uses visual encodings for node and link differentiation, with little effort given to constructively

encoding the attributes and characteristics of the entities. The same degree of differentiation could be shown by one or two properties. As it is, node color, shape, type size and style, and line color, weight, and style are all used to nearly no effect.

### **6.5.2 Inconsistent encoding**

Inconsistent encoding, a violation of the principle of Informative Changes, can radically impede otherwise good diagrams. Figure 5: Wall Street Follies, on page 15, again provides us with a great poor example.

Because labels inconsistently encoded, the reader is required to read the labels on every entity to determine its attributes and relevance. Consistent encoding would allow readers to quickly perceive the patterns, and then efficiently extrapolate meaning to the balance of the diagram. This is discussed with other examples in section 4.3 starting on page 43.

### **6.5.3 Example: Organization chart with inconsistent encoding**

The organization chart show in is complex. It displays roughly six different dimensions of information:

1. organizational hierarchy, indicated by position or color
2. membership in named unit, grouped into boxes
3. membership in named area, indicated by color of unit box and placement
4. job title, head count, vacancy, and other text
5. job duties (subject specialist, references duties), indicated by symbol
6. other job classifications (resource pool, part time, librarian, vacancy), indicated by symbol or color

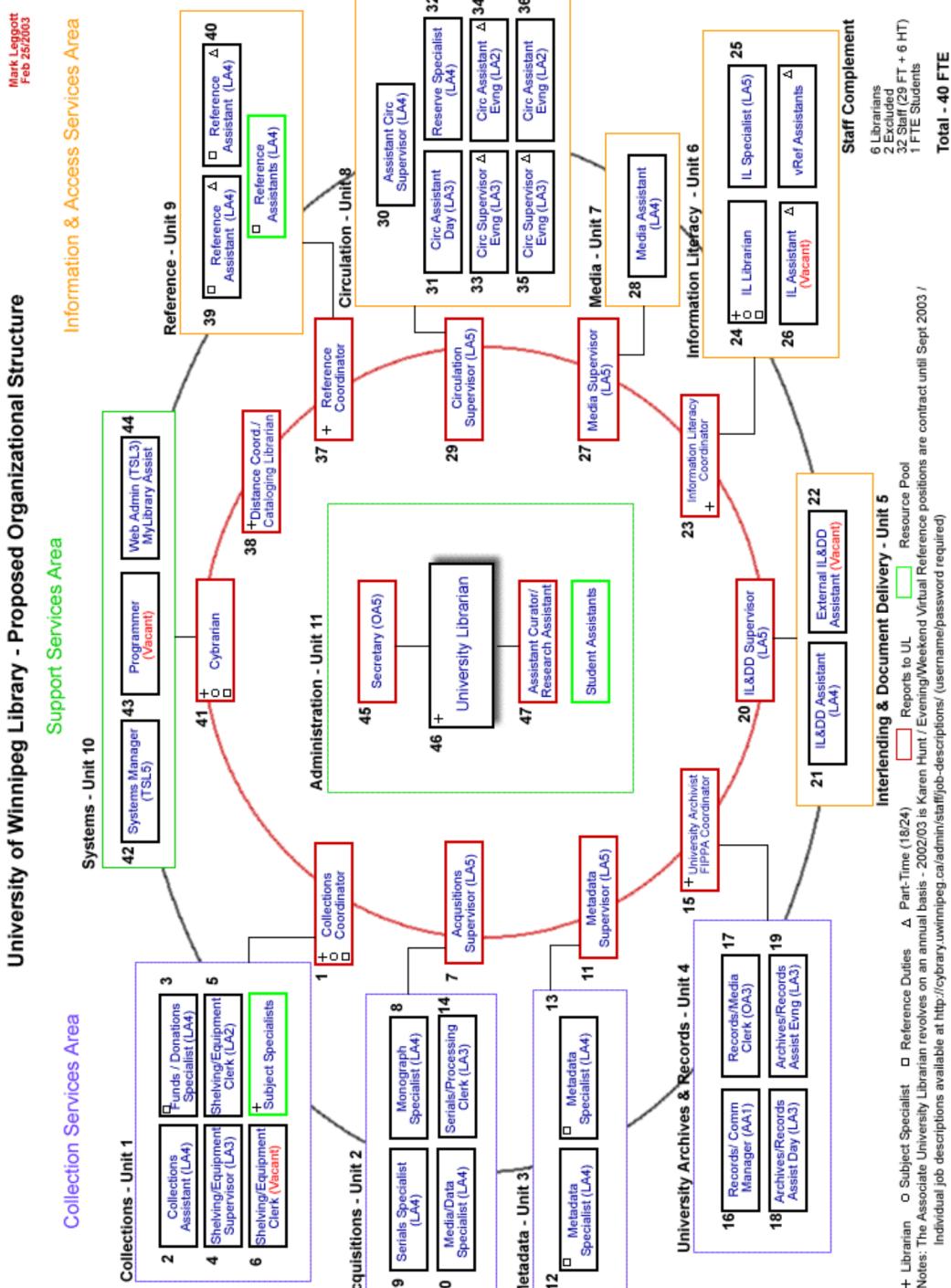


Figure 31: Organizational Chart with Inconsistent Encoding

As in Figure 18, the BSc diagram, using single encoding properties to encode multiple characteristics presents a problem to the reader, as they cannot easily determine the meaning of variations in a single property, say color. In this case color is used to indicate hierarchy, area membership, and other job classifications, and symbols are used to indicate job duties and other job classifications. Further complicating matters, the symbols have no inherent meaning, and must be decoded by the reader. Hierarchy is sometimes indicated by distance from the center, sometimes by box color, and sometimes by links. The large curved lines connect otherwise unrelated jobs or groups that have no connection other than they share similar levels of hierarchy. Unit titles are inconsistently placed, and it is sometimes difficult to tell which unit a title refers to. Finally, unit placement, which indicates area membership, isn't consistent, and unit color, which redundantly encodes area membership, isn't applied to the various unit supervisors and coordinators.

A more consistent version of this diagram, presented in Figure 32, addresses all of these issues. Hierarchy is made explicit by lines and enclosure into areas and units. The area and unit groupings are unambiguous, the use of color is consistent, and the labels are clearly attached to their respective units. Resource pool employees are colored to indicate their different membership. The various encodings of duties and job classifications have been replaced with consistent, coherent use of letters that naturally map to the function that they encode.

The consistent use of the various encoding methods (color, position, text) yields a diagram that is easier to quickly extract information from, and will likely be easier to maintain as the organization changes.

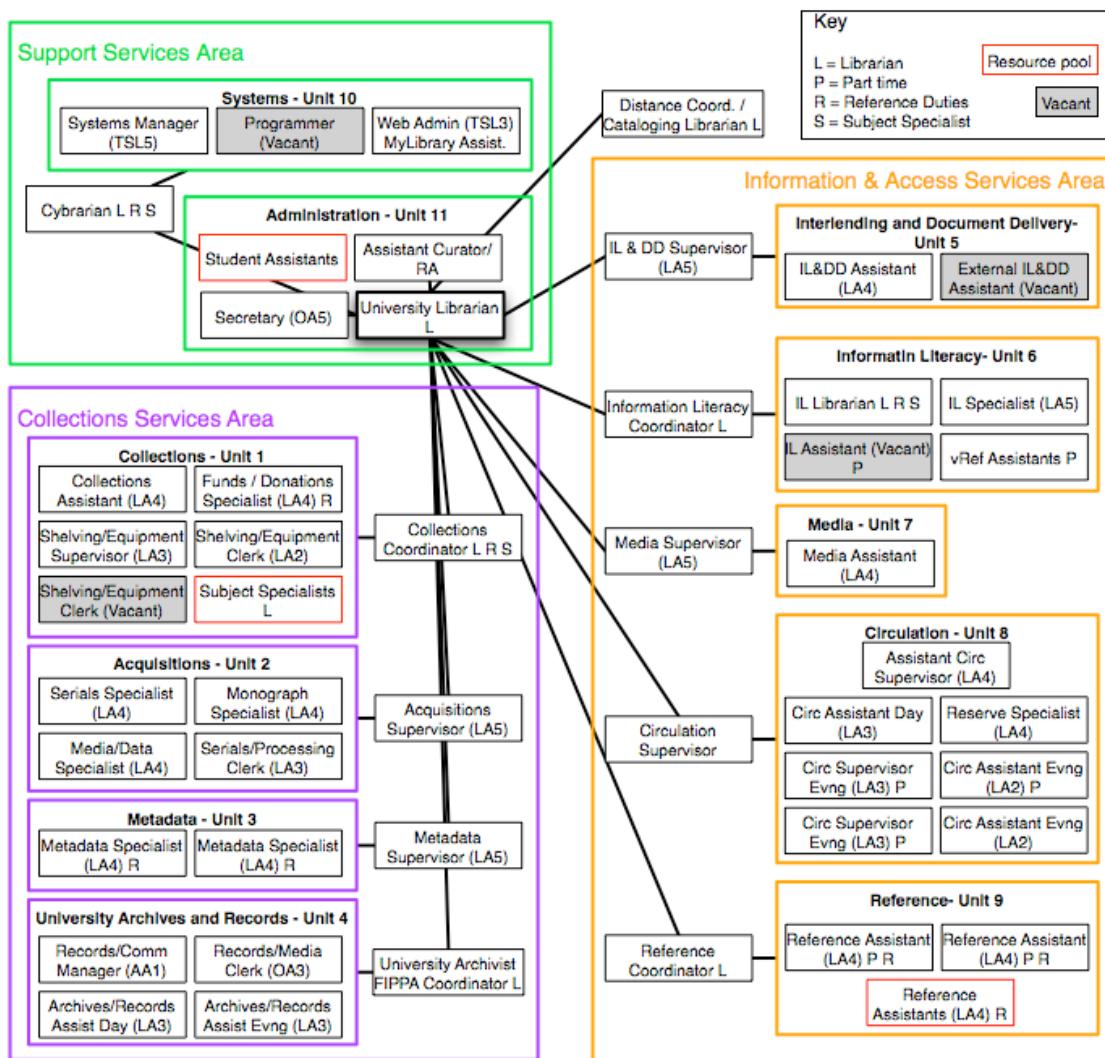


Figure 32: Improved Library Org Chart

## Conclusion

In this thesis I have presented a method for quantifying the complexity of diagrams, and discussed some of the challenges facing designers of complex qualitative diagrams. I have presented five fundamental principles and have explained how they are relevant to the diagram design process and can improve the resulting diagrams. The principles were provided with sufficient depth and context so that a diagram designer can apply them as quick rules-of-thumb, or can use them to guide more in-depth analysis of particular design decisions.

Next steps could include a few different ways of fine-tuning the system by getting feedback from users in academic, experimental, and professional contexts. For example, I would like to see how the notion of dimensions of complexity enhanced a classroom conversation about diagrams. The benefit of the design process and guidelines could be quantified by evaluating diagrams drawn by novices before and after instruction in this system. These novice-generated diagrams could be tested in different contexts, and with different audiences with various goals. Professional users could discuss the degree to which improved diagrams facilitate work flow and knowledge transfer. Each of these evaluations could provide insight into which portions of the system are most useful and beneficial to diagram designers and users.

Naturally, my hope is that this system will prove itself useful to a broad collection of diagram creators and users.

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