Knowledge Visualization

Problems and Principles for Mapping the Knowledge Space

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MSc Thesis Dissertation
Submitted in partial fulfilment of the degree of
Master of Science in Digital Media
International School of New Media
University of Lübeck, Germany
June 2004

Abstract

With the advent of digital communication technologies, an enormous quantity of information can be stored and transferred. But with increasing possibility comes increasing complexity. As indicated by the dissatisfaction often experienced by users of information technology, current systems of accessing, organizing and navigating information are proving insufficient. Visualization, the representation of information on an interactive map, is a strategy to make more efficient use of cognitive resources when processing complex information. The design of mapping systems which can not only present information but communicate knowledge, however, is lacking a comprehensive theoretical foundation. This would account for the following issues: the nature and structure of information and knowledge, the strengths and limitations of the cognitive and perceptual systems, the social context of knowledge work and visual discourse, the semiology of representation, and the implementation and assessment of interface metaphors. This thesis explores aspects of these key areas and presents a state-of-the-art in visualization strategies which are classified according to three informational meta-structures: *complexity* (paths), *context* (relationships), and *dynamics* (change). Analysis of these systems facilitates the distillation of the following principles for knowledge visualization design: *map*, *optimize*, *stabilize*, *adapt*, and *digitalize*.

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Acknowledgements

For showing me the importance of having a great vision,
Hubertus von Amelunxen.
For guiding me to ask the right questions,
Pierre Lévy.
For inspiring me to dig deeper and look higher,
Richard Scotti.
For sharing in the never-ending adventure of building a new school,
my fellow students, faculty and administration at ISNM, 2002-2004.
For exposing me to the universe of design and visualization,
Gui Bonsiepe.
For illustrating how terrific a teacher can be,
Frieder Nake
For structural support and sound advice for this thesis,
Joachim Hasebrook.
For endless discussion and design tutelage,
Uli Schmidts.
For sharing in the sounds of the thesis room,
Gerd Stodiek.
For keeping me sane and strong through the thesis process,
Birte Großkopf.
For unconditional support and love,
Alan, Lin, Andrew and Vanessa Judelman.

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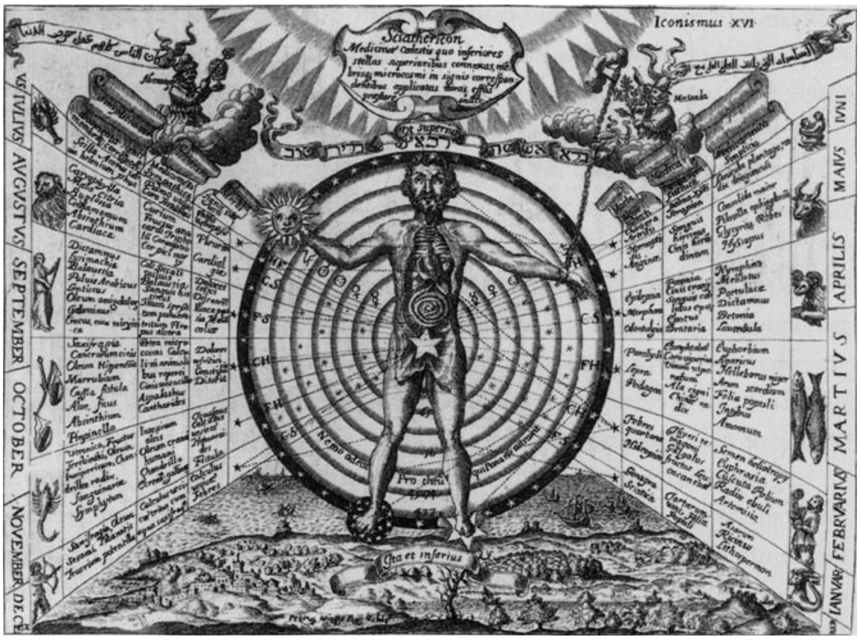
“the real voyage of
discovery

consists not in seeking
new landscapes,

but in having
new eyes.”

Marcel Proust
“The Captive”, *Remembrance of Things Past*



1.1 Athanasius Kircher, Cosmic Man, 1671

***image source*: Stafford 1999, 165**

1 Introduction

"Cyberspace. A consensual hallucination experienced daily by billions of legitimate operators, in every nation... A graphic representation of data abstracted from the banks of every computer in the human system. Unthinkable complexity. Lines of light ranged in the nonspace of the mind, clusters and constellations of data. Like city lights, receding..."

William Gibson, *Neuromancer*, 1984

The proliferation of digital communications technologies has created a massive space for the storage and transfer of information. Connected through global networks, millions of computer users are sharing and distributing information contained in documents and stored in archives. The access and availability of information has exploded in the last decades and will continue to do so in coming years. The technology is rapidly evolving in sophistication; becoming faster, smaller, more mobile, and less expensive every year.

But with increasing possibility comes increasing complexity; the support by digital and other material technologies of this complex and dynamic information space has not necessarily made more efficient the communication of knowledge. Today's media technology provides a framework in which knowledge can be archived and transmitted, but current systems of accessing, organizing and navigating information are proving insufficient. Across personal and professional cultures, people are devoting increasing time and energy to filter and process masses of information in order to extract meaningful knowledge. Current information systems often present unsolicited and uncontextualized details which make it difficult to verify and put information to use. An improvement in strategies for organizing and presenting information is required to reduce the dissatisfaction often felt by even experienced information seekers. A great challenge today is not necessarily to produce new knowledge, but to develop improved modes of working with and making sense of that which we already have.

One strategy to make more sense of a complex information space is information visualization, the visual presentation of information on an interactive map. Visualizations take advantage of visual and spatial cognitive powers to reduce the cognitive effort required for processing complex information. The mapping of data parameters to location, colour, or form produces images which can reveal objects, patterns and relationships which remain undetectable when presented as lists or tables. Visualizations can ideally be tools of thought and learning, extending cognitive processes by allowing active exploration of a knowledge space.

Growing out of information and interaction design and inspired by traditional cartography, information visualization is an exciting research domain with great potential. Current research is laying the foundations for this area, developing techniques and algorithms for certain applications and discovering strategies to make the most of the limited display and processing powers of current computers (Card 1999; Chen 2003a). Information visualization interfaces, after some years of evolution, will likely utilize sophisticated visual and interactive techniques to provide an efficient and effective basis for the communication of knowledge. It is possible that, in the future, the fundamental interface that links humans to cyberspace is a two- or three-dimensional visualization of the global knowledge space (Lévy 2003).

The advantages and potential of visualization are evident, but current system development is constrained by practical, theoretical, and technical limitations. While the hybrid of scientists, designers, and artists performing visualization research are producing many creative and interesting experiments, these developers could greatly benefit from a more solid theoretical foundation to support design. In particular, there is no design theory which accounts for the strengths and limitations of the cognitive and perceptual system, the nature and structure of information and knowledge, the social context of knowledge work and visual discourse, the semiology of representation, and the implementation and assessment of interface metaphors (Chen 2003a, 31). A significant challenge is to find modes of coherently and comprehensibly translating the multi-dimensional complexity and dynamism of abstract knowledge onto a map.

This thesis addresses some of the key issues that will support the development of a theory of knowledge visualization design. By assessing the nature of knowledge and problems of its representation, and obtaining an overview of contemporary visualization techniques, a set of principles for design has been developed. These principles, and the theoretical background which supports them, provide an initial framework for the visual communication of knowledge.

1.1 Summary of Contributions

Knowledge visualization design would be facilitated by an improved theoretical foundation. This thesis makes several contributions to this need by defining and integrating key research which will encourage the development of this theory. The primary contributions have each been organized into a chapter in this work:

> *Knowledge*: This chapter looks at the nature of knowledge and how it emerges from information and data. It details how human cognition is supported by technology and summarizes the strengths and limitations of cognition and perception in visual learning. It concludes by describing the influence of media on the knowledge space and defines a model for contemporary knowledge work.

Visual Knowledge: This chapter outlines information visualization and describes how it reduces the cognitive effort required to process complex information. It then gives a brief overview of the domains that have contributed to the evolving science of visualization and discusses the power and language of mapping.

*Survey of the State-of-the-ar*t: This chapter is a survey of the state-of-the-art in information visualization, in which a selection of interesting visual and interactive techniques are described. The examples are classified based on the meta-structures that each system reveals: *complexity* (topology, path), *context* (relationships), and *dynamics* (movement, change).

Designing Knowledge Visualization: This chapter presents sources of inspiration for finding appropriate metaphors and strategies to visualize complexity. It also summarizes the techniques from the survey, and finishes with the presentation of design principles which were generated from a synthesis and analysis of the previous sections. The principles capture key aspects in which visualization can support cognition and reveal knowledge structures, and are named *map*, *optimize*, *stabilize*, *adapt*, and *digitalize*.

The conclusion reviews the contributions of this document and summarizes areas requiring research for future knowledge visualizations.

2 Knowledge

"...clarity and excellence in thinking is very much like clarity and excellence in the display of data. When principles of design replicate principles of thought, the act of arranging data becomes an act of insight."

Edward Tufte, *Visual Explanations (1997)*, p9

As alluded to by Tufte, the clarity of a visual (and interactive) design is closely related to the awareness a designer has about the nature of thought; including an understanding of what knowledge is, the properties of cognition and perception, and the theory of learning. Before getting into the specifics of visualization in later chapters, this chapter accordingly introduces and clarifies important aspects of knowledge, cognition, and media.

The first section, *Knowledge and Cognition*, defines knowledge and distinguishes it from data and information, and explains how it is supported by technology. Aspects of cognition and perception are presented which give insight into the nature of learning. The second section, *The Knowledge Space*, expands on the cultural relationship between technology and knowledge and elaborates on the processes involved in knowledge work.

2.1 Knowledge and Cognition

2.1.1 Describing Knowledge

> *"Knowledge is a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information. It originates and is applied in the minds of knowers. In organizations, it often becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms."*
>
> Tom Davenport, *Working Knowledge* (1998), p5

Knowledge is a complex and enigmatic phenomenon. Tom Davenport's comments reflect the mix of mental, experiential, and procedural forms that knowledge can take. Gaining knowledge can be described as a problem of integrating experience, as described by Alfred North Whitehead (Sowa 2000, 348, original from *Essays in Science and Philosophy*, Philosophical Library, New York 1937):

> *"Human knowledge is a process of approximation. In the focus of experience, there is comparative clarity. But the discrimination of this clarity leads into the penumbral background. There are always questions left over. The problem is to discriminate what we know vaguely."*

As these two different perspectives on knowledge indicate, defining knowledge or forcing it into a model is a difficult if not impossible task. The nature of knowledge and the mind is an age-old question that has been endlessly pondered upon and theorized by philosophers, monks, scientists, and artists. Still today this issue drives research in the fields of psychology, cognitive science, linguistics, neuroscience, religion, philosophy, design, and others. Each of these disciplines uses different functional notions of knowledge to serve the needs of their discourse, but the quest for the development of a more universally applicable model may never be realized.

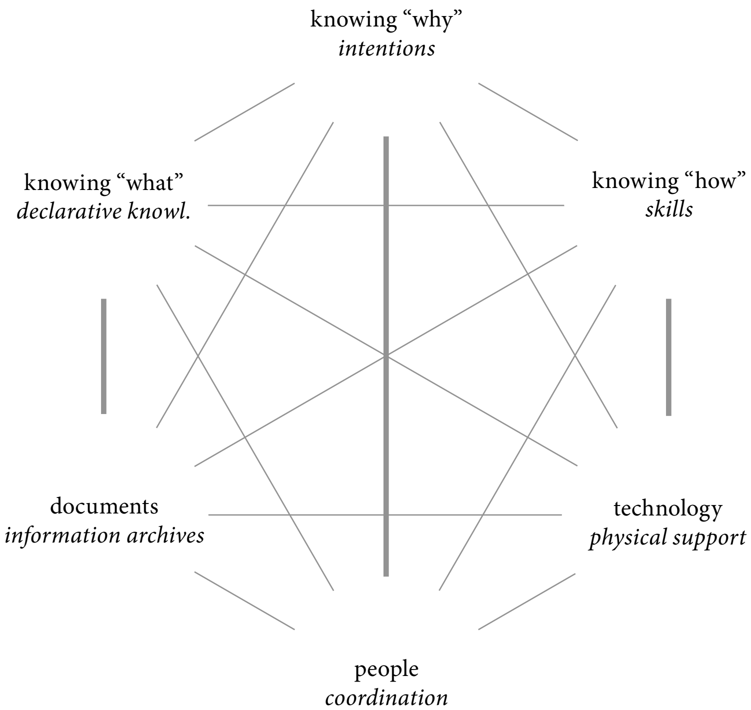
Nonetheless, to develop improved modes of understanding and working with knowledge, it is both possible and necessary to sketch it and its characteristics. Knowledge can be described as a "*dynamic organization of memory*", and while it exists in the mind as an inner cognitive process, it is supported and augmented by technology and social organizations (Lévy 2004a).

There are three different interdependent types of knowledge, all of which play a role in the coordination of human action. These qualities of inner cognition can be summarized as knowing *what*, knowing *why*, and knowing *how* (Lévy 2004a; Jonassen 1993). Knowing *what*, termed *declarative* knowledge, can be represented in (but not take the form of) documents in all communication media (spoken, written, printed, etc.). This declarative knowledge can be articulated with language (i.e. made explicit) and thus feeds intelligent and creative discourse such as those in the arts and sciences. Knowing *why* refers to knowledge which addresses the notion of the reason or meaning of some phenomenon. It orients and defines the intentions of human action, and relates to the system of values propagated by societal institutions. Knowing *how*, or *procedural* knowledge, is the tacit skills that develop only from experience. Forms of procedural knowledge, such as the ability to perform surgery, dance ballet, or speak a foreign language, are difficult to articulate (i.e. represent) and manifest in the professions of individuals.

All three of these types of knowledge are necessary to coordinate action (Lévy 2004a). Without representable declarative knowledge (knowing what should be done), communication and learning become impossible. Without clear goals or intentions (knowing why we should do something), an action would not be consistent and coherent. Without the skills to perform some task (knowing how to do something), an action is ineffective.

While each type of knowledge exists within the human mind, each is interrelated with and supported by external phenomena. *Declarative* knowledge is representable and takes semiological form in documents. Knowing *why*, the intention or will of our action, is socially coordinated by societal institutions. Finally, procedural skills require communication or material technologies to be successfully executed as an action.

The interrelationships between the different types of knowledge and the documents, social networks, and technologies that support them are illustrated by the following diagram (redrawn from Lévy 2004b):



2.1 This image illustrates the dynamic interrelationships between human internal cogntive processes (the top three elements) and the external knowledge represented in documents, augmented by social groups, and supported by technological materials and infrastructure. This complex system can be termed the *knowledge space.*

The thicker lines illustrate which of the top three elements are more directly supported by which of the bottom three.

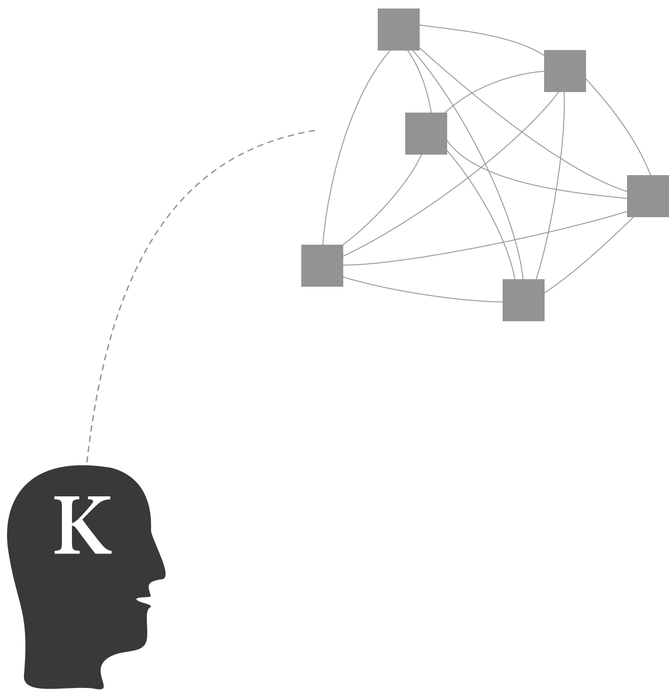
Image adapted from Lévy 2004b.

This image illustrates the dynamic interrelationships between human internal cognitive processes (the top three elements) and the external knowledge represented in documents, augmented by social groups, and supported by technological materials and infrastructure. This complex system can be termed the "knowledge space". It includes the three types of knowledge (knowing what, how, and why), people, the knowledge embedded in documents, and communication media or other technologies which facilitate transfer or application of knowledge.

2.1.2 Cognition and Learning

Although knowledge manifests both inside and outside the human mind, cognition is an internal mental process. While is no less complex or easier to model than the concept of knowledge, in general it can be defined as the human capacity to learn, remember, act, and communicate. It is the contextualized and multi-dimensional network of associations, memories, and ideas that changes through experience. The paths through this network link certain objects based on semantic criteria such as similarity or difference. The architecture of this semantic network of thought *objects* is highly complex and dynamic and perpetually evolves in form. In the words of a prominent cognitive scientist, "*abstract concepts acquire their meaning not through direct associations with percepts, but through a vast network of relationships that ultimately links them to concrete concepts*" (Sowa 1984, 76).

2.2 Mental cognition as a semantic network of thought objects. This image is a severe reduction and does not account for the organic fluidity and multi-dimensionality of cognitive processes.



Cognitive Science has attempted to model the mind's semantic network with analysis of linguistic logic and syntax. This approach, however, has not successfully simulated human thought or natural language processes because it doesn't account for the semantic complexity and multi-dimensionalilty of cognition. This study has, on the other hand, provided insight and produced intriguing models to understand cognition. White (1975, from Sowa 1984, 76) stated:

> *"To discover the logical relations of a concept is to discover the nature of that concept. For concepts are, in this respect, like points they have no quality except position. Just as the identity of a point is given by its coordinates, that is, its position relative to other points and ultimately to a set of axes, so the identity of a concept is given by its position relative to other concepts and ultimately to the kind of material to which it is ostensively applicable…A concept is that which is logically related to others just as a point is that which is spatially related to others."*

These comments propose the structure of a semantic network to be organized based on the relative similarity or difference of concepts. It also introduces the notion of the representation of knowledge as a spatial structure, where spatial proximity relates to semantic proximity. This is an important concept for the visualization of knowledge, which will be addressed in later chapters.

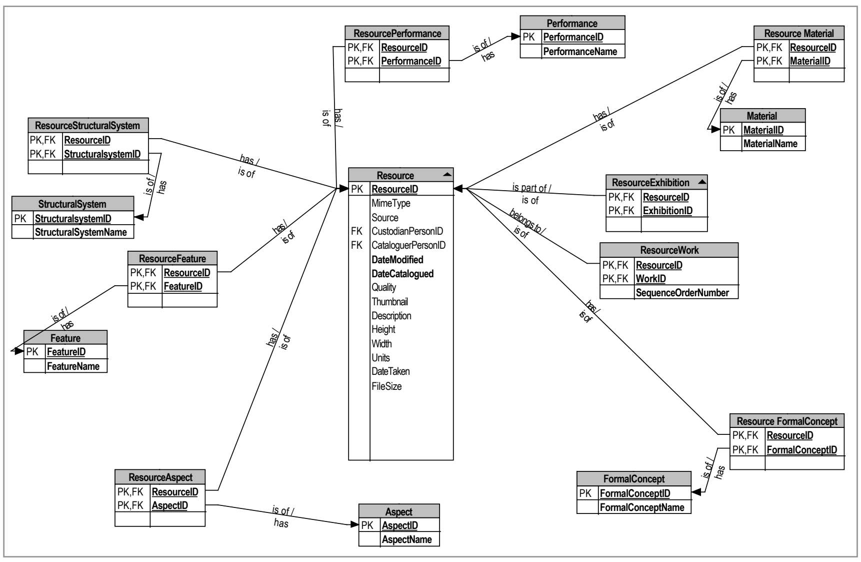
Several techniques have been developed by cognitive scientists to simplify and represent basic semantic networks (Jonassen et al 1993; Sowa 2000). These include hierarchical content structures (like a family tree), concept maps (like a database conceptual schema, fig. 2.3), and semantic maps (fig.

2.3 & 2.4 Two classic modes of representing semantic networks.

Left is a conceptual schema (for a database architecture design)

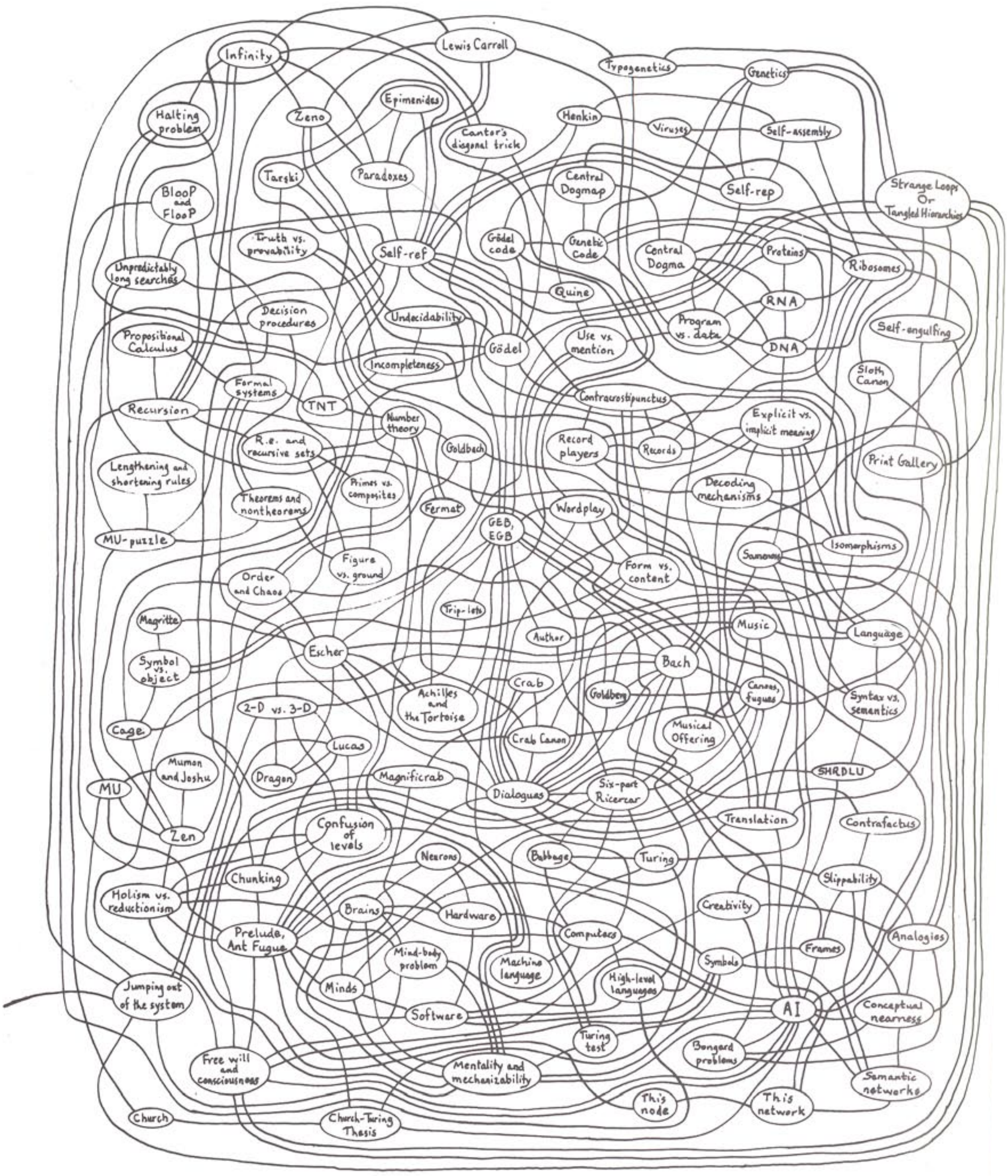
Right is a sketch of a semantic map, showing the relationships between ideas and interests of the artist. This thesis investigates other modes of visualizing these types of knowledge spaces.

Image sources:
Left: courtesy of Prof. Michael Docherty
Right: Hofstadter 1979, 370



2.4). Concept maps are often used to design the information architecture of a relational database, and semantic maps can be used for artificial intelligence natural language analysis.

Memory is the ability to recall paths through the cognitive web architectures using a system of stored (but dynamic) trails which connect associated thought objects in the mind. The more intense an experience, the more robust these trails become and the easier it becomes to recall a memory. This concept explains the deepening integration of procedural knowledge that occurs through experience. If we repeat an action (or thought) over a



duration of time, we eventually forget the (explicit) rules and act “without thinking”. We experience this when learning a new language or skill; the memory trails become burned into our mind over time.

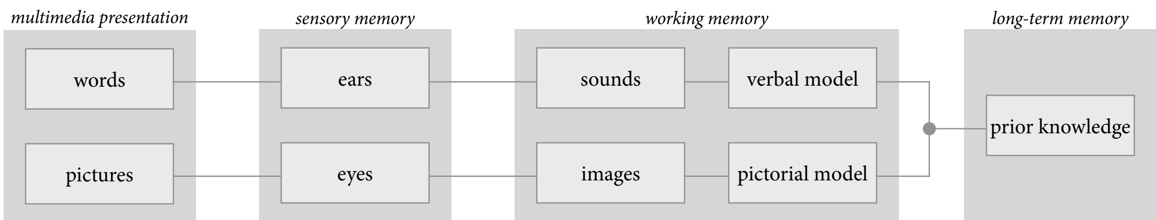
This integration of knowledge through experience is learning, which reveals new behavioural potential in an individual. There are many theories in cognitive psychology which postulate how learning occurs, each attempting to understand the dynamics of the perceptual-cognitive system and the integration of new information with stored knowledge.

A particularly relevant study to the development of visualization systems is the *cognitive theory on multimedia learning* (Mayer 2001, 41). This theory is based on three assumptions on how individuals learn. Firstly, the *dual channel* notion, which asserts that humans possess separate channels for processing visual and auditory information. Secondly, that humans have a *limited capacity* for the amount of information that can be processed in each channel at a time. Thirdly, that individuals learn by *active engagement* with cognitive processes such as the selection, organization, and integration of information.

The theory also asserts that there are three types of memory involved in multimedia learning: *sensory*, *working*, and *long-term*. Sensory memory holds images or words that enter perceptual senses (eyes, ears) for a very brief period of time. Working memory takes these images and actively processes them (by selection and organization) in conscious thought. Coherent mental models of incoming information are formed by integrating these active processes with previous knowledge, stored in long-term memory. The process is summarized in the following diagram.

2.5 Processes in the Cognitive theory of multimedia learning.

Image redrawn from Mayer 2001, 44



The theory outlines the *dual channel*, *limited capacity*, and *active engagement* assumptions in further detail. It explains the relations and functions of each of the dual learning channels (visual and auditory), describes the sources of cognitive load and the allocation of cognitive resources, and identifies the cognitive processes involved in active learning. These notions are important to acknowledge in the development of visualization systems as they are an explicit description of how individuals learn.

Cognitive load, in particular, relates to the mental effort required to engage with or process some information. Two sources of cognitive load during learning have been identified, *intrinsic* and *extraneous* (Sweller and Chandler as cited in Mayer 2001, 50). Intrinsic cognitive load depends on the inherent complexity or difficulty of the learning material. Extraneous cognitive load depends on how the information is organized and presented to the learner. An *intuitive* interface features a coherence (or ideally transparency) of interactional elements such that "*irrelevant or inefficient cognitive processing*" (Mayer 2001, 50) is reduced and the informational content can be concentrated on. More cognitive resources would then be allocated to support the intrinsic cognitive load and less is required for extraneous processing.

Another important notion for visualization design is understanding the nature, strengths and weaknesses of the perceptual system. Gestalt psychology, developed in the early twentieth century, describes the tendency of the visual system to perceive coherent patterns in a visual field (fig. 2.6). This involves the grouping of visual elements (colours, forms, etc.) based on certain visual criteria and helps to explain how images are seen as a whole, not as a collection of individual parts. An example phenomena is the recognition of a face, which occurs before individual elements (eyes, nose, ears) are inspected. Gestalt perception is grounded in laws of similarity, proximity, continuity, symmetry and closure, as well as the distinction of figure and ground (foreground from background) (Ware 2000, 203). The following image illustrates several optical phenomena which are explained by Gestalt theory.

2.6 Gestalt effects can influence how an image is perceived, as illustrated by the illusory effects of these examples.
image source:
Tufte 1990, 60

Based on these and other models of human cognition and perception, learning systems (including visualization) can be designed to work with the flow of cognitive processes. Key points for system design include the include the reduction of cognitive load and the active engagement of the learner (from the cognitive theory for learning), and revealing patterns over details (from Gestalt theory).

2.1.3 Data, Information, and Knowledge

> *"Where is the life we have lost in living? Where is the wisdom we have lost in knowledge? Where is the knowledge we have lost in information?"*
>
> T.S. Elliot, *The Rock* (1934)

> *"Wissen kann man mitteilen, Weisheit aber nicht. Man kann sie finden, man kann sie leben, man kann von ihr getragen werden, man kann mit ihr Wunder tun, aber sagen und lehren kann man sie nicht."*
>
> Hermann Hesse, *Siddhartha* (1922)

To further understand the complexity of knowledge and its interrelationships with cognitive, social and technological systems, it is useful to describe the different forms it can take at different periods of its communication or creation. A model (albeit a simplification) can be found in the description of the relationships between data, information, and knowledge.

The processes of learning and understanding involve progressing along the continuum from data to information to knowledge. To understand the processes involved in producing knowledge from information and information from data , the first step is to describe characteristics of each of the three elements and the system they produce together. While there is no universal model of this system as perspectives and definitions change coming from engineering, design, linguistics, or philosophy, it is nonetheless a useful exercise to draw from each of these areas to distil descriptions. Figure 2.7 presents a collection of descriptive notions to produce what could be termed the data-information-knowledge (DIK) continuum.

	data	information	knowledge
processes (along continuum)	collect analyze	organize represent	contextualize apply
properties	quantifiable disordered raw	processed structured patterned	understood verified discussed
examples	spreadsheets timetables facts	visualizations reports instructions	actions processes stories
context	none	low	high
ambiguity (in communicated or articulated form)	none	low	high
entropy	high		low
relation to individual's desire (clarity of purpose)	low		high

2.7 The data-information-knowledge continuum.

The content for this table was inspired by several sources, including Bonsiepe 2003; Nake; Scotti 2004; Shedroff 1994)

Data are measured numbers, statistics or facts, the disordered details that are collected into timetables and spreadsheets. Information can be found in instructions and reports and is produced once data is given context by semantic analysis and organization. Knowledge is built experientially through the application and verification of information, as functionality of information is integrated such that appropriate action can be taken.

This triadic set of relationships is not new to the digital age, but is an established philosophical idea. From a semiological perspective, Charles S. Peirce's triadic system of classifying signs approximates the interrelationships between data (*Firstness*), information (*Secondness*), and knowledge (*Thirdness*) (Nake). To quote from Peirce's description of the three types of signs (1891, from Sowa 2000, 60):

> *"First is the conception of being or existing independent of anything else. Second is the conception of being relative to, the conception of reaction with, something else. Third is the conception of mediation, whereby a first and a second are brought into relation."*

Immanuel Kant's *Critique of Pure Reason* (1787) contains a system of categories, including three in a group called *Relation*: *Inherence*, *Causality*, and *Community*. Inherence is a characterization of an entity's explicit qualities such as size, colour, or shape. Causality defines the cause and effect relationships that connect a set of entities. Community is the third category whereby the previous two are contextualized (Sowa 2000, 61). Both Pierce and Kant's triadic categorizations map appropriately to the increasing contextualization from data to information to knowledge.

One of the difficulties in clearly defining data, information, and knowledge is that they don't exist as distinct entities but in a continuum. Knowledge emerges from information by its contextualization, application, and social exchange. The gradual change from data to knowledge is approximated in figure 2.7 in terms of processes, properties, context, ambiguity, entropy, and desire.

The processes row contains actions that are performed within the continuum, from collecting data through to utilizing knowledge. These actions shape data into knowledge or vice versa. The processes relate to the different type of knowledge work, which will be discussed in section 2.2.2.

A fundamental distinguishing factor along the DIK continuum is *context*. Context is introduced into the system by discovering relationships in data or putting application rules to information. Data, generated by measurement, is usually presented in raw form as a vaguely ordered set of numbers or words. Information is produced when the data is organized into some broadly applicable (i.e. global) categories or order, such as a sorted list. As the information is integrated by an individual, it becomes personally contextualized in the person's conceptual semantic network. This explains the trend for the scope of context to be reduced (from global to personal) as information becomes knowledge.

The increasing personalization of context relates to the *ambiguity* of the message in communicated form, which increases from data through to knowledge. Data takes the form of numbers, statistics, or words, all of which can be notated in original form without compromise to detail. A computer can take data without any translation or abstraction and process it, count it, copy it, or analyze it. Producing information from this data requires a level of interpretation both in categorizing and presenting the information. This interpretation requires decisions to be made, and while they give meaning to the data, they introduce a degree of ambiguity into the system. Information can be distilled and presented through media, and upon utilization and verification becomes knowledge. To communicate knowledge it must be first abstracted from the individual's personal context and represented in language or expressed through some action (this is more relevant for procedural knowledge than declarative). The translation is done by an individual in an effort to send out message into the world; the semiological ambiguity of the representation of knowledge is what makes communication so challenging.

It should be stressed that the notion of data having less ambiguity in communicated form does not imply that data itself is unambiguous. Data is generated from the measurement and observation of some phenomena. The process of measurement immediately introduces ambiguity based on the design of the measuring device used and the perspective of observation. Even the presence of an observer has an influence on the data that is gathered. This notion is mathematically embedded in Heisenberg's Uncertainty Principle, which essentially states that there is a degree of ambiguity in any measurement due to the influence the observer has on the system. The previous point regarding the ambiguity of data, information, or knowledge refers exclusively to the processes required to communicate these elements. Once hard data has been generated, it can be articulated with no loss or translation. Both information and knowledge, on the other hand, must be interpreted or translated to some extent before they can be expressed.

Entropy is the degree of disorder in a system. A principle of physics states that the entropy (disorder) in the universe tends to increase, and as such to place order into a system requires energy and work. In informational terms, as data is contextualized into information it is ordered into a system of relations (Bonsiepe 2000). Once integrated as knowledge, entropy is again reduced, as a set of application rules constrains the information into an even more structured state. The entropy metaphor highlights the notion that energy and work are required to integrate data as information and then create knowledge. In designing a communication system, the modes of interaction and engagement with data, information, or knowledge should be implemented to demand the least possible cognitive effort to place order on information.

The final row in figure 2.7 describes the value of some piece of information in relation to an individual's needs or desires. If a person is not hungry, then information about where to obtain food is not valuable and remains as data. If hungry, on the other hand, then information about satisfying the hunger desire would be of great value, and thus likely be integrated as knowledge and acted upon. This relates to the notion of intentionality, in that the greater an individual's need to fulfil some desire, the more focused is his/her intention to act in such a way that this is fulfilled.

A challenge in designing systems for working with information (such as visualization) is letting the user specify the information they need and mapping data in such a way that context is revealed. Since the raw material of the computer is hard data (text characters and numbers), a danger is producing visualizations which reiterate the data but do not give it a relational context. A well-designed system exposes context and pushes the learner as far as possible along the DIK continuum with the least possible cognitive effort. These notions are addressed in further detail in section 5.3.

2.1.4 Classifying Knowledge

The analysis and organization of information are essential processes for producing knowledge from data and information. This requires some system for measuring relative similarity and difference among information objects. An ontology is a classification system for organizing information based on semantic criteria or relationships. Whether working at organizing a small set of data or a great body of knowledge, the objective is to add structure, context, and meaning to the system. But the difficulty is that a set of related objects can be compared on many levels and the selection of which criteria to use is often a subjective rather than an objective choice. To quote Charles Sanders Pierce:

> *"The task of classifying all the words of language, or what's the same thing, all the ideas that seek expression, is the most stupendous of logical tasks. Anybody but the most accomplished logician must break down in it utterly; and even for the strongest man, it is the severest possible tax on the logical equipment and faculty."*
>
> Charles Sanders Pierce, *letter to editor B.E. Smith of the Century Dictionary* (from Sowa 2000, 492)

Pierce recognized that by logic alone, it is very difficult to classify ideas (or knowledge). For example, based on what criteria could a group of dogs be sorted? Height, weight, length of hair, name, age, species, amount of food consumed, etc., are all valid category systems. In the mind, we are able to simultaneously keep each of these categories in mind when assessing a group of dogs. This emphasizes the multi-dimensionality of thought and the difficulty in using some ontological system to classify the mind's semantic web.

2.8 A human can immediately put each of these chairs into context of use. But based on what criteria could they be classified? Size, mobility, weight, comfort, purpose are just a few examples. It would be very difficult to capture the essence of each item with just a few classification terms.

image source: Sowa 2000, 350

A basic form of ontology is a classification system, a set of categories into which data can be sorted to establish it into a context. Information designer Nathan Shedroff has come up with a set of classification criteria (adapted from Saul Wurman) from which he claims any set of data can be arranged.

These categories are (Shedroff 1994):

Alphabets
Locations
Time
Continuums
Numbers
Categories
Randomness

Most data can be organized according to at least one of these systems and it would establish a relational system (i.e. information) for analysis. These categories, however, tend to be one-dimensional (i.e. alphabetical organization are lists from A-Z) and are mere approximates the mind's multi-dimensional semantic network. The above categories are useful for classifying data into information, but more sophisticated ontologies are necessary to organize the multi-dimensionality of knowledge.

The practical problem of classification goes beyond the quantity of criteria used to classify some knowledge system; the order of magnitude of interrelated concepts in the mind is immeasurable. Given this complexity, the challenge to map out a semantic space (of the mind's semantic network) is a great task. Researchers across disciplines of philosophy, cognitive science, neurology, linguistics, information science, and others are using various approaches to discover the nature of knowledge and its relation to mental processes.

The development of sophisticated ontologies is likely to become a primary research objective in coming years to address the need for greater organization of knowledge. The next generation internet, often referred to as the "semantic web", will semantically organize information based on ontological frameworks (Berners-Lee 1999).

2.2 The Knowledge Space

2.2.1 The Media Sphere

> *"Because in the past transmitter and storage media were in short supply, for a long time we lived outside knowledge. Today, by contrast, we move in the space of knowledge, in the permanent virtual present of knowledge-satiated spaces, yes, we are inundated with knowledge."*
>
> Michel Serres, *Literature and the Exact Sciences*, 1988

The knowledge we carry in our minds is left as traces by our actions in the world around us. We speak according to what we know, we travel in paths guided by cognitive maps (Kitchin 2000), we work by implementing past experience into a current situation. With each action we perform, our knowledge is extracted from our cognitive semantic network, decontextualized, and put out into our environment in a transformed state. To reiterate Tom Davenport's definition (section 2.1), "*[knowledge] becomes embedded not only in documents or repositories but also in organizational routines, processes, practices, and norms.*" (Davenport 1998, 5).

As previously explained, knowledge is represented in documents, augmented by social groups, and supported by technological materials and infrastructure (figure 2.1). Inherent in this description of knowledge is the significance of social and technological (i.e. cultural) factors in determining the dynamics of the knowledge space. The needs or desires of a particular society and the technology it has available to communicate and fulfil these needs has a large influence on its cultural forms.

The configuration of communication media, or the "media sphere", has been shown to have great influence on the cultural forms that emerge (McLuhan 1964). To quote Neil Postman, "*We do not see...reality...as 'it' is, but as our languages are. And our languages are our media. Our media are our metaphors. Our metaphors create the content of our culture*" (from Castells 1996, 356). McLuhan stated that "*the personal and social consequences of any medium...result from the new scale that is introduced into our affairs by...any new technology*" (McLuhan 1964, 10).

Modes of communication change depending on the unique properties of each media. Some media are more durable (writing carved in stone), some are easier to transport (writing on paper), some work better from a close distance (camera) and others render distance and time irrelevant (email). In terms of distribution, some media are for communicating one-to-many (radio, tv), some one-to-one (telephone), and still others many-to-many (internet).

The following table summarizes characteristics of culture and language in different historic media spheres.

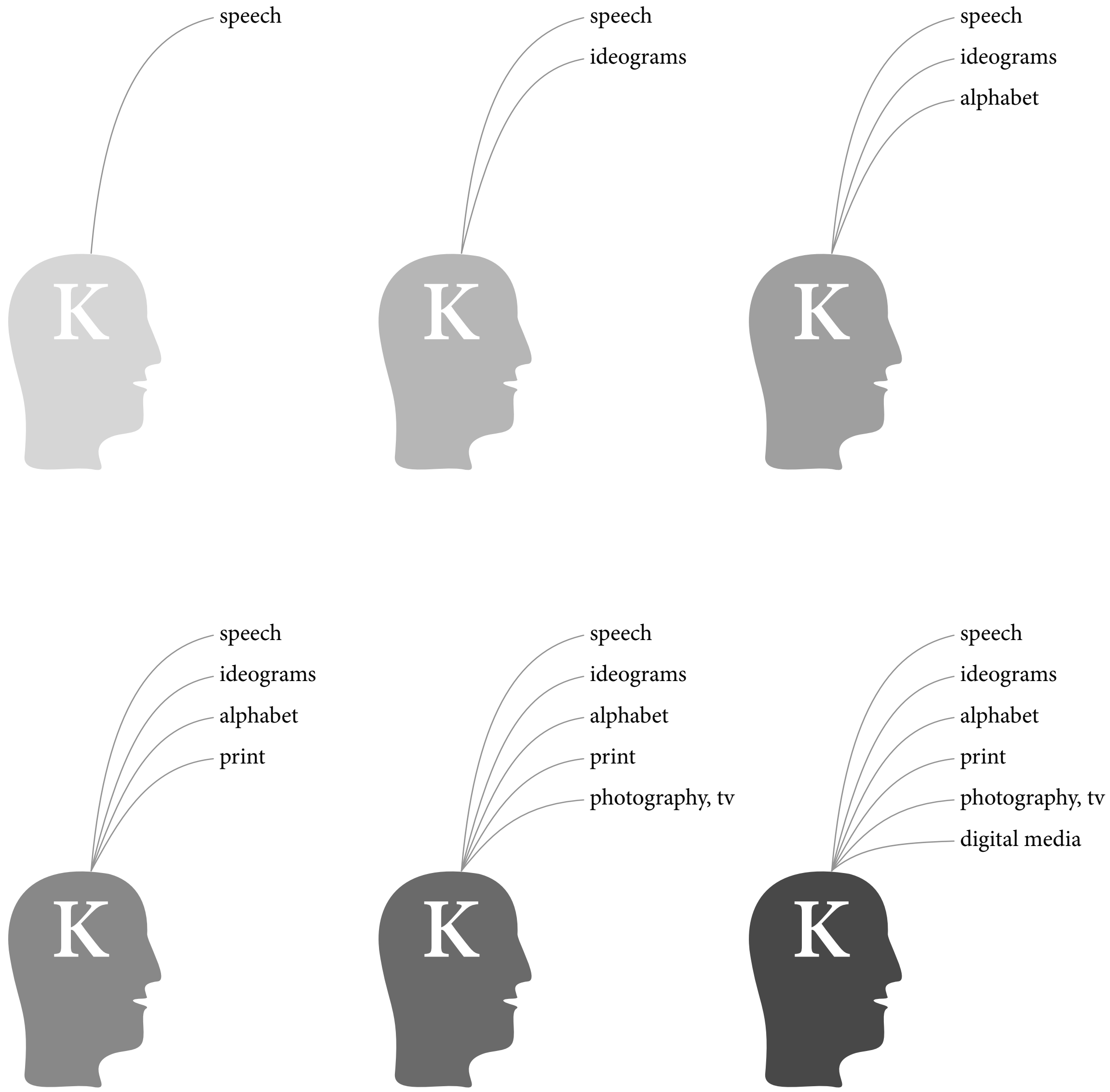
2.9 Characteristic of culture and language in different media spheres.

Adapted from Lévy 2004b; source for dates is Stephens 1997

newest communication technology (with beginning of relevant time period)	cultural characteristics	language characteristics
speech (100,000 BC)	complex institutions religion technique symbols music hunting and gathering learning by imitation and experience	oral transmission myths rituals memory inscribed in physical matter (sculptures, tools)
ideograms (3000 BC)	cities state law complex religions with a clergy agriculture cattle breeding schools	visual symbolic systems representing concepts
alphabet (700 BC)	citizenship monotheisms buddhism money commerce universities science	universal writing system representing sounds
mass media (1500) *printing press* *photography* *telegraphy* *telephony* *cinema* *radio* *television*	modern democracies reform liberalism human rights industrial revolution world market capitalism libraries experimental natural sciences	technical self-reproduction of images and sounds
digital media (cyberspace) (1970) *media convergence* *interactivity* *global network*	megalopolis network planetary cyberdemocracy religious convergence biosphere's evolution monitoring knowledge economy nature of information	ubiquity of signs interconnection of messages autonomous activity of software

The media sphere, by determining modes of knowledge access and processing as well as channels for its exchange and distribution, has great influence on the dynamics of the knowledge space. Oral cultures were mostly composed of nomadic tribes who passed knowledge by word of mouth often in the form of story or myth. Thus there was little means of giving knowledge physical form; most of it was "archived" in the minds of the population and could only be transferred in the form of speech as quickly as a person could move from one location to another. Certain ritual objects, such as sculptures, carried symbolic knowledge through generations. The advent of ideographic and alphabetic writing enabled the codification of religious or state law and was accompanied by the sophistication of large religions and the separation between urban and agricultural lands. With the advent of paper, knowledge became more mobile and could be reproduced as quickly as manuscripts could be hand-copied. The masses were excluded from much of the knowledge space, as an elite group of literate intellectuals and religious leaders maintained and controlled the written material. The printing press enabled a mass reproduction of books and preceded the arrival of the renaissance, public education, the industrial revolution, nationalism, institutionalization of cultural bodies and eventually capitalism. The existence of mechanically reproducible books encouraged a greater distribution of knowledge in libraries and archives. Mass media such as telegraphy, photography, telephony, radio, and television have each contributed to radical changes in the formats and dynamics of knowledge distribution by introducing the technical transfer of image and sound. Figure 2.10 (following page) summarizes particular media available at various stages of technological evolution. It illustrates that each new media form is introduced as a supplement (not replacement) to older media.

The knowledge space, as the media sphere, is in continual flux and evolves as new media technologies are introduced. The rapidity of the development and integration of digital network technologies over the last ten years has produced arguably its most radical reconstitution. Written, oral, and audiovisual media have been integrated into a single convergent system and distributed in an interactive network. Bypassing limitations of expensive and elaborate equipment, anyone with a computer, basic software and an



internet connection can instantaneously and cheaply reproduce, distribute, and produce documents anywhere in the global network. This has altered and effectually complexified the knowledge space by exponentially increasing the following factors:

types of media in concurrent use
exposure time (immersion) to media sphere
total number of documents (amount of knowledge stored in media)
rate of information flow
exposure to irrelevant (undesired) information
rate of obsolescence of information
access to content production and distribution technologies

2.10 Media spheres at various stages of the evolution of media technology. How might the access and transfer of knowledge change given these different communication media?

As communications technologies evolve and new modes of communication are implemented, the rate of change in these factors continues to increase. For example, documents become obsolete far more quickly than before; some books are relevant only a few years, journals a few months, and websites a few weeks or days. But generally outdated material remains in the media sphere and must be sifted when searching for information. A century ago books retained relevance for longer and the publishing industry produced less volume.

Furthermore, the amount of information that is available and needs to be processed is exponentially greater than in previous media spheres. With the convergence and networking of mass media on the internet, we have instantaneous and ubiquitous access to images, films, texts, etc. from all over the world in any subject area. In the course of a day, information is received in conversation, on the radio or television, from advertising, on the internet, and in newspapers. More media is being churned out by the spectacle machine (see a study called "*How much info*" at *http://www.sims.berkeley.edu/research/projects/how-much-info-2003*), and much of it is disposable or recycled. Publishing content on the web is not constrained to editorial approval but is open to anyone with minimal technology and skills.

The increasing complexification of the knowledge space, in combination with the limitation of current information systems, often lead to what information designer Saul Wurman calls "information anxiety" (Wurman 1990). In the new, evolving and complexifying architecture of the knowledge space in the digital era, we need new modes of managing and interfacing to the knowledge space.

2.2.2 Knowledge Work

"Es ist nicht genug zu wissen, man muss auch anwenden (It is not enough to have knowledge, one must also apply it)".

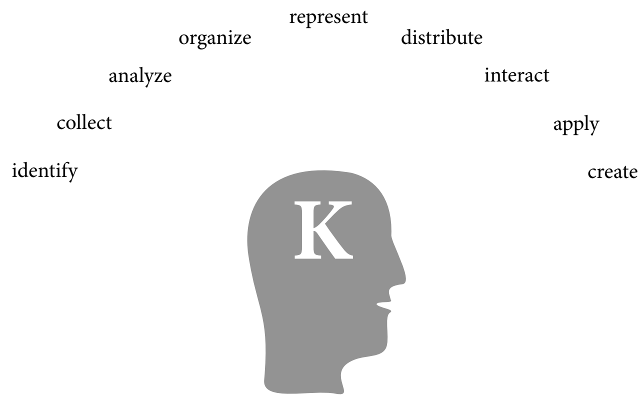
Johann Wolfgang von Goethe

Goethe's comments still apply today, but may be more pertinent if reworded to say something like, "It is not enough to have information, one must also know its quality, location, and application". There has been to date an enormous quantity of produced and documented expert knowledge, but too often necessary knowledge isn't available in the right place at the right time in order to be put into action. A great challenge today isn't the production of new knowledge, but making sense of what we already have.

Previous cultures, in particular in pre-digital times, may have faced a problem of information access. Obtaining quality information required getting hold of heavy and expensive physical media such as books, journals, audio recordings, etc. In today's media sphere, the amount of freely available information on the internet alone (not even considering books or other media) is enormous. The constraint is no longer access, but filtering, finding, and assessing the quality of information content.

Due to limitations of contemporary systems for structuring and navigating the knowledge space, much useful knowledge remains obscured under mountains of irrelevant, redundant, or low-quality informational content. As much as the sciences and arts have made incredible discoveries and generated a great body of knowledge, this knowledge only gains value through its sharing and implementation. For this reason, recent years have seen an exponential increase in attention to developing and implementing systems for working with knowledge.

To reflect upon on the requirements for knowledge systems, it is useful to name some key processes in knowledge work. Figure 2.11 shows important stages in the targeting, communication, application and subsequent creation of knowledge (phases inspired by Liebowitz 2001, 4, and visualization specialist Ramana Rao *www.ramanarao.com*).



2.11 Knowledge work processes

These actions, read from left to right, form a cyclical model which summarizes key steps in what could be called *knowledge work*. In relation to the DIK continuum above (figure 2.7), each action in this cycle, from *identify* through to *create*, requires an increasing degree of context and personal integration. The first step is the identification of possible sources and types of knowledge. Once identified, a collection (i.e. gathering, or "data mining") of a desired type of data occurs. This data is analyzed (i.e.semantic analysis, or "text analysis") and then organized based on some ontological classification system. The information is then prepared for presentation in a communicable form, being mapped to some representation (i.e. document, visualization, list, book, etc.). This document or representation is subsequently distributed to be accessed and interacted with (i.e. viewed or read). After interaction, the information is personally integrated such that it can be applied in action. Through repetition and experimentation with this action new knowledge is created by the individual.

Digital communications technologies increasingly mediate intellectual, economic, educational, recreational and social exchange, producing a contemporary culture sensibly termed the "knowledge society". Knowledge work and systems to support it have become primary cultural necessities. The understanding of the stages in knowledge work and the development of systems to automate or facilitate these processes supports the communication and creation of knowledge.

It should be asserted that computer technology is deeply integrated into every step of the knowledge work cycle. Data mining, semantic text analysis, interactive visualization, internet distribution and eventual use of the software application all require computer processing, networking, and multimedia capabilities. The technical expertise required to set up these systems means that computer scientists and engineers have most of the responsibility for implementation. The research and development from these highly technical disciplines usually builds systems which require the user to adapt technical conceptual models and interfaces. This explains much of the difficulty encountered by non-technically inclined computer users.

In the effort to design a technocultural knowledge work infrastructure that supports the humans that use it, the discipline of *cognitive design* gains enormous responsibility. To quote information design pioneer Gui Bonsiepe, "*Designers...structure action spaces for users through their intervention in the material and semiotic universe*" (Bonsiepe, 1997a). Communications architects or information designers, who have an understanding of both technological constraints and human needs, should be responsible for the conception, design, and implementation of each individual process in the knowledge work cycle. They would also integrate the processes together to optimize the access and flow of knowledge. If this can be achieved, than the introduction of ambiguity and distortion as each step in the cycle passes on to the next is reduced and technology users (i.e. communicators) would experience less dissatisfaction. Much of the frustration and anxiety felt on a personal, institutional, and cultural level relate directly to the inadequacy of current systems in serving cultural needs. A great deal of research and design (not to mention economic gain) will occur in the twenty-first century to improve modes and systems for knowledge work.

3 Visual Knowledge

Given the insight of the previous chapter into the relationships between knowledge, cognition, and media, this chapter looks specifically at the visual representation of knowledge. The first section, *Information Visualization*, clarifies problems with current information interfaces and explains the alternative strategy of visualization. It concludes by summarizing the problems and limitations being faced by current researchers and designers. The second section, the *Language of Visual Knowledge*, takes a brief look at the foundational roots from which visualization has emerged. It then gives an overview of the visual language developed by one of the most important of these founding disciplines, cartography. The section concludes by briefly assessing how mapping changes in the digital medium.

3.1 Information Visualization

3.1.1 Problems with Current Information Interfaces

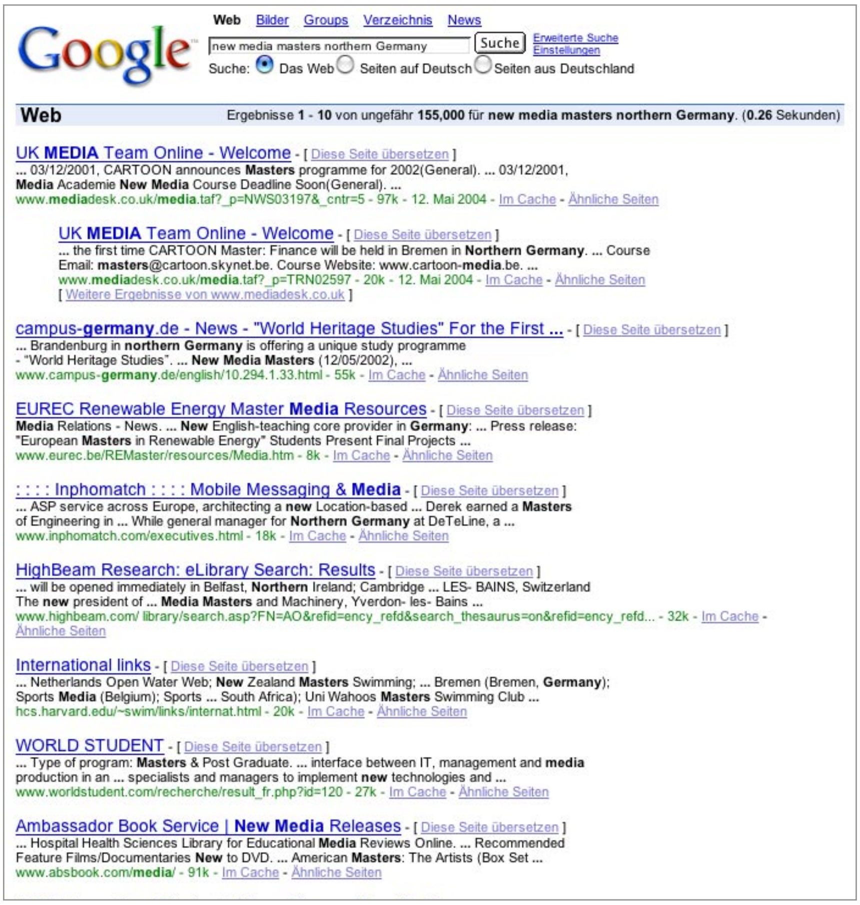
The knowledge space is growing and complexifying; embedded knowledge (as information) is increasingly distributed in fluidly reproducible and transportable digital or analog (print, broadcast media) documents, permanently and ubiquitously available on the internet. The giant digital ocean of information and the ease of reproduction and distribution of digital documents is an enormous resource, but its chaotic (non-)organization makes accessing the right information problematic. Knowledge that is concealed in some untraceable documents is worthless, it gains value only in its application and ease of transfer.

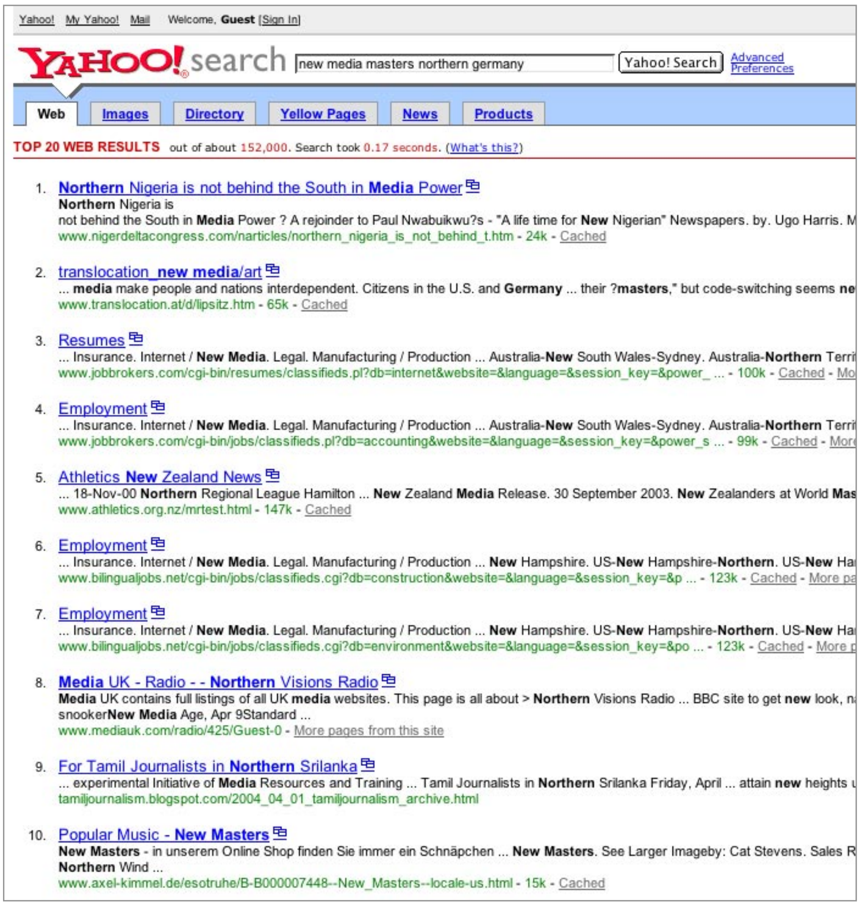
The current technological infrastructure which supports knowledge work does not yet optimize the transfer of knowledge. Systems are lacking for semantic structuring and navigation of the knowledge space. An example is the use of contemporary search engines to access information on the internet. To find a particular document we must deduce the keywords that associate to it (meeting the machine on its terms), and then hope that it ranks favourably (based on some opaque criteria) and appears high on the list of search results. Reading the long lists returned by search engines requires high intensity cognitive engagement (i.e. time and energy) to scan for the desired item. It is a common experience that desired documents cannot be found and remain obscured behind unrelevant or commercial websites. With the enormous quantity, ubiquitous availability, ease of reproduction, interactivity, and multimediality of digital documents, new methods are required to appropriately manage this complexity.

Current search, navigation, and orientation interfaces for digital documents are based upon an organizational paradigm inherited from the mass media era. The popular Yahoo classification system, for example, classifies digital documents into fourteen categories (such as *News and Media*, *Education*, *Arts and Humanities* or *Computers and Internet*). Using the directory to find a particular piece of information can be difficult, as many websites could fit into several categories. For example, where would the website for a new media masters program in northern Germany be? It could be in "Germany Regional" or "Germany Education" or "New Media Education" or even "Postgraduate Education". Finding a site using the directory requires the user to perform a kind of reverse logic to figure out where the organization would have registered the site. Even Google, the most popular search engine, ranks results not based on semantic relevance but on the quantity of links to the site. This produces lopsided results, often favouring commercial and high-traffic websites in search rankings and obscuring the desired page far down a list. In general, the search and navigation process tends to be confusing and imprecise (fig. 3.1).

One reason for this imprecision is that a web-directory such as Yahoo is a rigid hierarchical classification. The abstraction of human knowledge into such a hierarchy is a reduction of the multi-dimensional inter-weaving associations in a semantic network of conceptual relationships. A categorizational classification structure gives sufficient search capability for print library collections, as the Dewey Decimal or Library of Congress system have proven their utility in aiding targeted research. Print media, however, which does contain an enormous body of knowledge, is static, not interactive, costly to reproduce, and spatially constrained. With the advent of digital media, on the other hand, the semantic complexity due to the increased volume, density, and fluidity of documents renders rigid categorization and long text lists of results less than optimal.

From a semiological perspective, the evolving virtual knowledge space of interactive, dynamic, and networked digital documents produces a flowing ocean of signs which form interrelated documents. To avoid an information chaos and enable a manageable knowledge economy, this complex and organic semiotic space requires adapted semantic systems to facilitate the organization of information on more understandable or "human" terms. Perhaps in the future we will be able to register the website for the aforementioned new media masters program not based on a single chosen category, but based on its relative position within a large network of semantic relations. Once this kind of a system is in place to organize the semantic space, it will be possible to produce useful visual interfaces to represent it and facilitate orientation, navigation, searching, and surfing through it.





3.1 A–B Screenshots for Yahoo and Google search results for "*new media masters northern Germany*". Notice that the search results have to do with anything from Nigerian media politics to athletics in New Zealand. They unfortunately, however, have nothing to do with the International School of New Media, a new media masters program in northern Germany.

Images captured on May 14, 2004

3.1.2 Visualization: Taking Advantage of Visual-Spatial Cognition to Process Complex Information

"Maps are graphic representations that facilitate a spatial understanding of things, concepts, conditions, processes, or events in the human world"

Harley and Woodward, *History of Cartography, Volume 1* (1987)

The presentation of complex information spaces by text-heavy interfaces is less than optimal; information visualization provides an alternative. A visualization is the reduction and translation of complex semantic and topologic interrelationships of the knowledge space to an interactive visual map. These maps are digital descendants of cartography and information graphics, and extract visual strategies from visual art and graphic design. Taking advantage of the digital medium's ability to process data, display 2D or 3D graphic environments, update in real-time, and respond interactively to a user's actions, these maps can expose salient details and provide multi-dimensional feedback to aid orientation and navigation through information. The interactivity and dynamicism of the digital medium, in combination with principles of good information graphic design (Tufte 1983), combine to create a platform for the development of sophisticated visualization paradigms.

Visualizations are information maps, and act as a kind of representation and simulation of the semantic space. The potential of simulation as a cognitive aid to assist in solving complex problems has been reflected on by cognitive psychologist Claude Lamontagne (Lamontagne 2002, 13):

> *"It is the technique of computer simulation, a still little-recognized, absolutely revolutionary technique which is pole-vaulting us into a quantum leap in improving upon our stocks of available reflection-empowering techniques, these most precious means of extending our mental abilities beyond the confines of our ever-moving, slowly and lazily unfolding, and so hopelessly easily distracted line of thought...[simulation is a] powerful reflection-empowering technique, one that would transcend the lifelessness of the written word, and bring it to life ."*

The critique of the cognitive system as "lazy" is perhaps a hyperbole, but the statement emphasizes the power of simulation in aiding cognition by "extending our mental abilities". Ideally, an interactive visualization is both a representation and a simulation; it translates the abstract complexity of large data spaces into sensual and spatial form, provides visual cues to conceptual structures and supports memory (Ware 2000, 335). Visualization takes advantage of and supports spatial reasoning, gestalt perception, memory, and decision making. A well-designed visual interface, to a digital archive, for example, has the potential to provide (Chen 2002, 2):

reduction of (visual) search time
deeper comprehension of complex data sets
revealing relationships otherwise unnoticed
enabling multi-perspectival views on data

Many studies have been done to describe and measure how visualization amplifies cognition in working with a complex information space. Some of this research is summarized in the following table (Card 1999, 16).

3.2 How visualization amplifies cognition of complex information spaces.

cognitive enhancement	example
increased cognitive resources	high-bandwidth hierarchical interaction (combining high spatial resolution and wide aperture) (Resnikoff 1987)
	parallel perceptual processing (as opposed to linear text)
	offload work from cognitive to perceptual system (Larkin and Simon 1987)
	expanded working memory (Norman 1993)
	expanded storage of information (i.e. maps)
reduced search	locality of processing by grouping informational elements (Larkin and Simon 1987)
	high data density (Tufte 1983)
	spatially indexed addressing (Larkin and Simon 1987)
enhanced recognition of patterns	recognition instead of recall
	abstraction and aggregation (Card, Robertson, Mackinlay 1991; Resnikoff 1987)
	visual schemata for organization
	enhanced patterns for values, relationships, trends (Bertin 1977/1981)
perceptual inference	visual representations make some problems obvious by supporting perceptual inferences (Larkin and Simon 1987)
	enable complex graphical computations (Hutchins 1996)
perceptual monitoring	monitoring of potential events if display is organized so that these stand out
manipulable medium	amplified user engagement as compared to static diagrams

A visualization can take advantage of interactive navigational techniques such as dragging, zooming, selecting, rotating, filtering and tracking. In this active navigation the user can probe the environment for significant visual or spatial patterns which may expose important information. Visual interfaces to complex information spaces allows the user to shift their cognitive load from reading and reasoning to the mental processes of visual and spatial cognition. This can reduce the cognitive effort required to mentally process a complex information space, and can expose elements and relationships that are difficult to see in lists or tables. It requires less cognitive effort, for example, to use a map to see the relative positions of landmarks in a city than to read a textual description of the same spatial information.

Visualization takes advantage of the human capacity for spatial reasoning; the ability of the mind to develop mental maps of a physical environment to facilitate navigation. Upon moving around a space, the mind produces a "cognitive map" of key paths and boundaries. This map describes the modes for spatial behaviour and decision making and learning new environments that humans require to navigate a space (Kitchin 2000). It includes the inverse ability to produce a cognitive model of a spatial environment from a map. The power of spatial reasoning was well-summarized by a GIS system designer (Kuhn as cited in Lango 2003, 45):

> *"Space is fundamental to perception and cognition because it provides a common ground for our senses as well as our actions. The constant mutual reinforcement of visual, auditory and tactile cues has developed our spatial cognition to an extent unmatched by any other domain. Perception, manipulation, and motion in space are largely subconscious activities, imposing little cognitive load, while offering intuitive inference patterns. Space has a strong inner coherence that proves useful for designing and combining metaphors."*

The innate and constantly reinforced human capacity for spatial reasoning makes the application of a spatial metaphor to information representation useful. By spatializing information into a 2D map or 3D virtual environment, a user need not exert full cognitive power to text or number crunching, but can take advantage of the sharpened ability for spatial navigation.

The utility of visual-spatial cognition to information processing is evidenced by the ubiquitous usage of cartographic maps and information graphics. Both cartographic and information maps are so common that almost everyone (within a modern cultural context) can read or at least gather basic information from them. Visualization is the application of these traditional graphic techniques, which have evidenced practicality and widespread literacy, to a modern problem and medium.

3.1.3 The Challenge of Visualization

The benefits of having a visual interface to navigate an information space are evident; is not unlike the advantage of having a cartographic map to provide expert guidance through an unfamiliar city. But there are key conceptual differences that makes visualizing knowledge particularly challenging.

Firstly, designers must consider not only static graphic codes, but also spatial navigation, interactivity narratives, and temporal dynamism. So the extensive visual language and strategies inherited from cartography and information graphics are just a beginning point; they must be extended into the digital domain.

Secondly, while static maps are representations and metaphors for physical and perceptible geographic space, knowledge is imperceptible with no physical analogue. Knowledge or information, and the semantic space in which they are represented, are abstract phenomena. The mind has no preformed images of informational object, and any representation occurs at an entirely symbolic level. As medieval maps charted the wild seas and ports as they were discovered, so knowledge maps can chart the traces of cognition and action of the knowledge space. But knowledge cannot be seen as land can, making the process of contextualization and mapping that much more difficult. The difference is emphasized by a cognitive scientist (Sowa 1984, 76), "*abstract concepts acquire their meaning not through direct associations with percepts, but through a vast network of relationships that ultimately link them to concrete concepts*". Mapping knowledge is the process of analyzing a knowledge space for meta-structures and meta-patterns and translating these structures to the visual domain.

How can the cognitive or semantic space be reduced, abstracted, and represented? How can abstract semantic concepts, such as *justice* or *peace* or *freedom*, be represented visually and mapped? More specifically, how should interfaces be designed to maximize both depth of engagement with the knowledge space and ease of operation? How can the embedded knowledge content of a digital archive be translated into a navigable environment? The answers to these questions should be accounted for by a design theory.

Thirdly, there are currently practical, theoretical, and technical limitations to the design and implementation of effective visualization systems (Börner 2004). This includes the necessity for mining and analysis systems which can process enormous amounts of data. Also required is data which is reliable, affordable, accessible, and of a readable and durable format. Considering the differences in terminology, standard ontologies are needed to describe and classify information by similarity and importance. Also essential are visual and interactive strategies to expose unanticipated relationships and enable interactive exploration of complex multi-dimensional information. And these strategies and metaphors utilized require modes of being assessed or tested for quality and functionality. Finally, the computer technology itself can improve in terms of speed, memory, display resolution, data transfer bandwidth, cost and availability.

These challenging issues, and the particular conceptual and implementational problems that go along with them, are among the driving concerns of visualization scientists. In the last five years, an emergent community of researchers from human-computer-interaction, cognitive science, interaction design, knowledge management, statistical analysis, and media art have produced an expanding body of experiments, discussion, and publications. The discourse is centred on current problems in producing clear, efficient, and adaptable systems: refining graphics algorithms, modes of representing and abstracting complexity, human-centred design models based on perception and cognition, integration of images and text, protocols for semantic ontological organization of data, and collaborative environments. Leading researchers listed the top problems facing this research area (Chen 2002, 229):

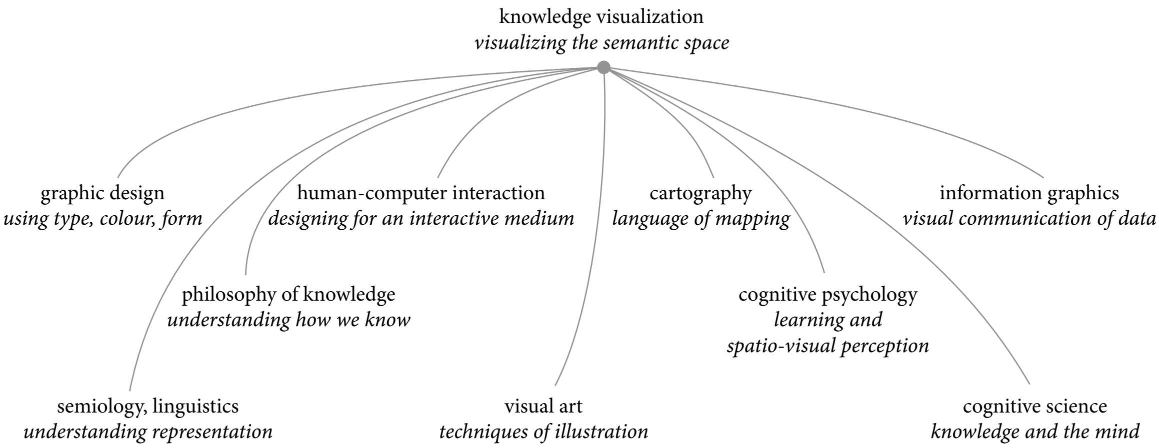
> *developing broadly applicable theoretical foundations*
>
> *developing a design toolkit of methodologies and taxonomies of proven techniques*
>
> *scalability (visual and informational)*
>
> *labelling (both typographic and semiological concerns)*
>
> *customizability of interface to user preferences and needs*
>
> *supporting collaborative work*
>
> *benchmarking and standardization*
>
> *evaluation methodology*
>
> *personalization of information to user's experience and context*

The space for innovation with this broad set of problems makes this an exciting research field, but due to the lack of proven principles and methodologies the success of systems is largely hit-and-miss. The quality of projects could also be improved by increased collaboration between researchers from the different perspectives of technical implementation, visual aesthetics and graphic design, interaction design, and cartography. As with many other research areas, there is unfortunately little infrastructure to support the exchange of ideas and transfer of skills in between these focused disciplines. The establishment of a design theory in the coming years will support researchers and improve systems.

3.2 The Language of Visual Knowledge

3.2.1 Roots of Visualization

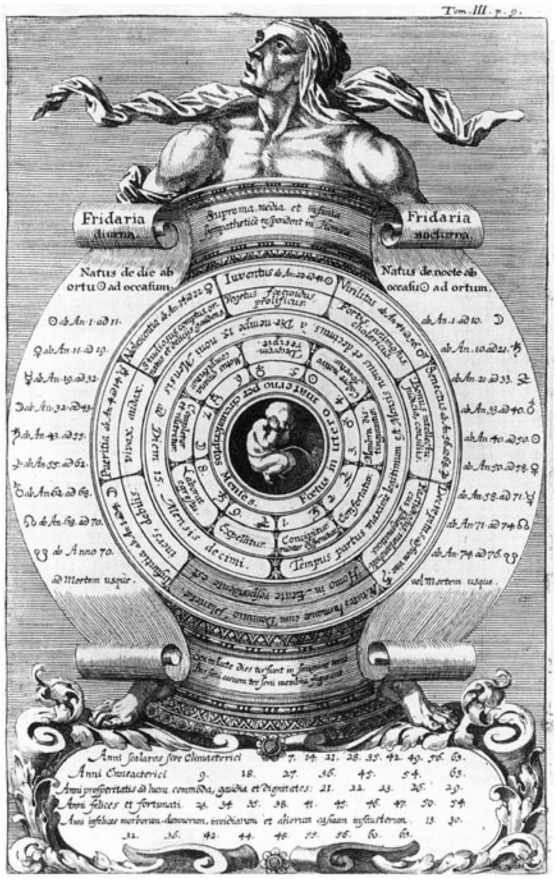
Despite the unprecedented dynamics of the digital medium, visualization itself is not new; it has emerged from centuries of practical and theoretical development. The following diagram gives an overview of the foundations of knowledge visualization from a broad historical and theoretical perspective:

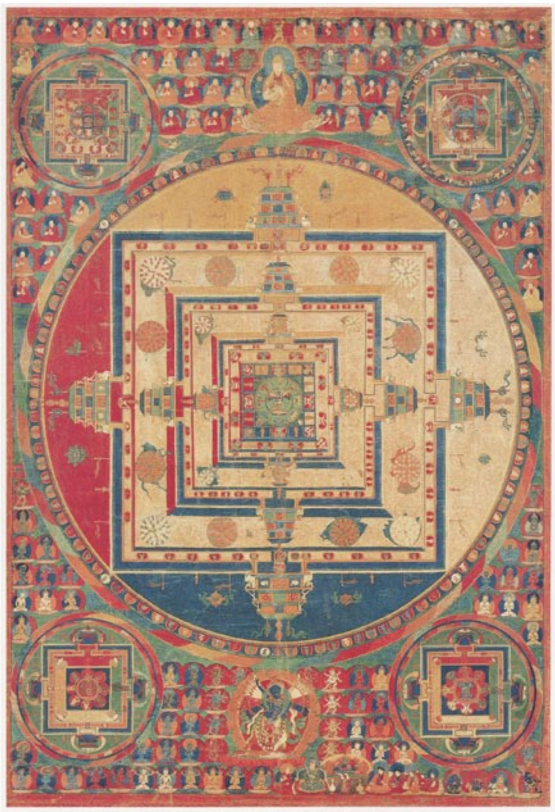


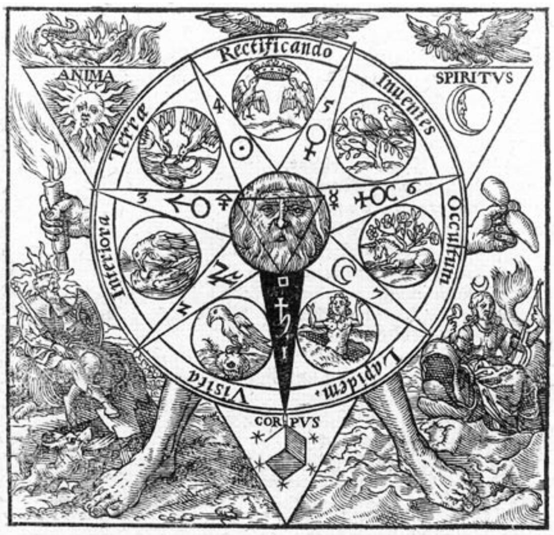
3.3 The foundations of knowledge visualization. Work from the indicated areas have provided a basis from which a new science can emerge.

The areas shown have contributed in various ways to the establishment the theory, techniques, codes, and literacy necessary for the cultural application of visualization. Specific contributions include the development of a visual language, a greater understanding of knowledge, insight into the psychology of learning, and human-centred visual and interaction design. While no reference is given to the development of technology (such as high resolution displays and graphics algorithms), it nonetheless provides the necessary technological infrastructure to support visualization systems.

Historically, the use of images to represent or communicate knowledge has been widespread. This practice has ranged from the utilization of images by medieval and eastern cultures as a support for meditation or memory (Carruthers 1998) to the representation by philosophers of the fundamental elements of nature. Following is a brief selection of images to give a sense of how different cultures and eras have approached knowledge and its visual representation.







3.2.2 The Power and Language of Maps

To work towards a theory of visualizing knowledge, a look at the function, power and language of maps is a useful step. Maps are graphic illustrations of structures, relations, and attributes of a space. They store and communicate knowledge, tell stories, describe place.

3.4 A–D ***Previous page.*** **Mapping the mind in different cultures and eras.**

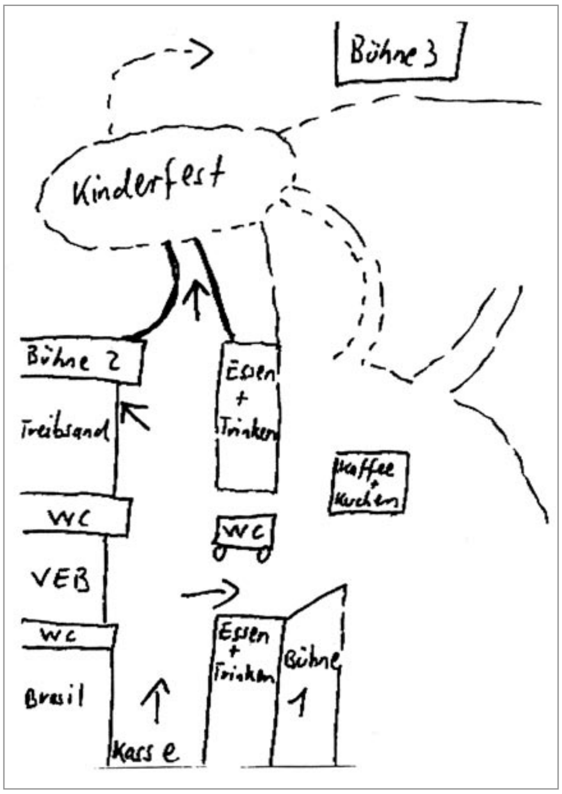
top left:
Ramon Lull, Tree diagram from *Arbor Scientiae*, Lyons 1515.
source: **Yates 1966, 188**

top right:
Johann Zahn, *Human Conception*, 1696
source: **Stafford 1999, 101**

bottom right:
Anonymous, *The Philosophical Work*, from *Occulta Philosophia*, 1613
source: **Stafford 1999, 59**

bottom left:
***Kalachakra Mandala*, Tibet, 17th Century**
source: **Denise Leidy and Robert Thurman. *Mandala*. London UK: Thames and Hudson, 1997. p99**

This map (fig 3.5), for example, was given out to attendees of an outdoor music festival (at the Walli-Alternative Lübeck, May 1, 2004) to find their way around the site. It is an imprecise sketch that looks like it was faxed and photocopied. While is consists only of some lines, arrows, and words, it actually contains a wealth of information.



3.5 A map given out to attendees of an outdoor music festival (at the Walli-Alternative Lübeck, May 1, 2004) to find their way around the site.

The map shows positions and relationships of the elements which can be cognitively mapped to orient and navigate in the space (Lynch 1960; Kitchin 2000):

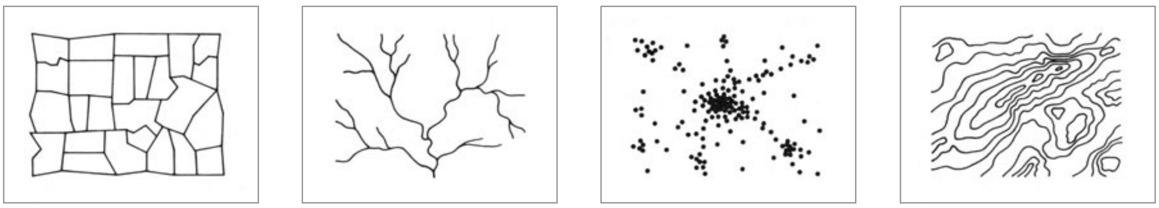
- *paths* - indicated by arrows and dotted lines
- *edges* - demarcated by solid lines
- *nodes and landmarks* - including toilets (WC), food and drink (Essen+Trinken, Kaffee+Kuchen), and performance stages (Bühne)
- *districts* - such as the children's play area (Kinderfest)

This map was produced by an amateur cartographer using simple technology (i.e. pen and paper), and requires no special training to read it. Herein lies the power of maps: almost anyone can read them (albeit some better than others) and learn something about a place, often without special instructions. The ubiquity of maps has proven their utility as communication and representation devices; they provide insight not just into places but also information, statistics, archives, social networks or historical events. Employing a graphic language of visual codes and symbols, the map transfers experience of a place to help others navigate or orient themselves within.

Mapping involves "*visualizing, conceptualizing, recording, representing, and creating spaces graphically*" (Cosgrove 1999, 1). The map, a "*spatial embodiment of knowledge and a stimulus to further cognitive engagements*" (Cosgrove 1999, 2), is a representation of a space. This "space" need not be a physical place, but can be a metaphor for non-physical phenomena as well. Knowledge, information, social interaction, economic transfer, biological system, or the historical evolution of an idea can all exist within this metaphorical "space".

The mapping of non-physical phenomena to spatial metaphors emphasizes the potential to find and represent the meta-structural patterns that govern them. Cartographic tradition make use of five sign systems (fig. 3.6) to represent these meta-structures (Wood 1992, 137):

matrix of areas - marking boundaries and divisions
network of channels - flow, communication, navigation
point distribution - positions of discrete objects
nested signs - continuums of equality
coordinate axis -a grid in which the other four systems are plotted



3.6 A-D Four cartographic sign systems. From left: matrix, network, distribution, continuums. Each of these four sign systems are bounded within a fifth, the coordinate axes.
***image source*: Wood 1992, 137**

A cartographer abstracts from the physical space and produces a representation using these five sign systems, and must constrain them within certain cartographic elements: *scale*, *framing*, *selection*, and *coding* (Cosgrove 1999, 9). Scale determines the proximity of perspective on a map, or how the mapped distance relates to real-world distance. The scale can be a great reduction, as in the case of a world map, or a magnification, as in the case of a map of human internal biology. Framing describes the content that fits within the edges of the map. Selection refers to which elements are represented or omitted. Coding alludes to how elements are represented, or how physical elements are mapped to visual parameters.

A physical space, as opposed to a knowledge space, lends itself to mimetic (iconic, based on visual likeness) representation; it is a real, tangible, perceivable space which can be translated into intuitively recognizable icons and symbols. Rivers, streets, and other physical elements on spatial maps have a real-world spatial analogy to which the representation bears resemblance. Influential urban planner Kevin Lynch calls this "imageability", which he defines as (Lynch 1960, 9):

> *"that quality in a physical object which gives it a high probability of evoking a strong image in any given observer. It is that shape, colour, or arrangement which facilitates the making of vividly identified, powerfully structured, highly useful mental images of the environment. It might also be called legibility, or perhaps visibility in a heightened sense, where objects are not only able to be seen, but are presented sharply and intensely to the senses."*

The non-imageability of knowledge is part of what makes it so difficult to visualize, but even imageable physical spaces cannot be objectively represented. Notwithstanding the mimetic likeness between a geographic map and a real place, a map is (like a photograph) not just an innocent reflection of the place. By choosing how, what, and why the place is translated onto the map, the cartographer simultaneously makes decisions, asserts boundaries, and tells a story. The signifier (map) and signified (space) are not equivalent, but make use of a semiological system operating on both a denotative (intrasignification, the language of the map) level and a connotative (extrasignification, the myth of the map) level. The following table summarizes ten cartographic codes which are contained in every map, but tend to be taken for granted by map viewers (adapted from Wood, 111):

signification level	code	description	relevance or task
intrasignification (language, denotation)	iconic	things or events depicted ("Main Street", "cancer levels in men")	inventory
	linguistic	names or labels ("Lübeck", "Atlantic Ocean")	classification, identification
	tectonic	scalar or topological spatial relationships	finding, navigating
	temporal	temporal scale ("king's travels from 1600-1604")	duration, historical relevance
	presentational	mode of coherently combining graphic elements (i.e. a colour scheme)	clarity, visual discourse
extrasignification (myth, connotation)	thematic	argument or domain of map	sets subject of the discourse
	topic	subject of map	assertion of existence of a particular place
	historical	reference to time frame of map	assertion of significance of a particular time
	rhetorical	orientation to cultural perspective	bias, style
	utilitarian	uses, functions of map	possess, claim, legitimize, name

3.7 Ten cartographic codes.

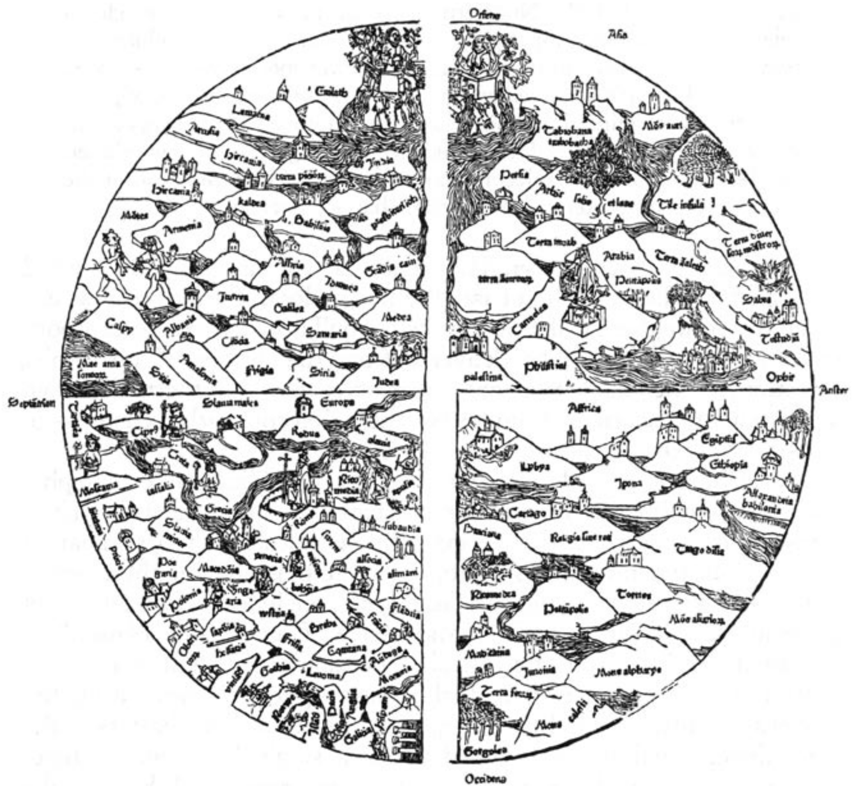
The map itself acts as a bridge between two semiological worlds: the *intra-significative* and *extrasignificative* (fig. 3.7). As explained by a theorist of cartography (Wood 1992, 116):

> *"The map [is] a focusing device between the domains of extra- and intrasignification...[it] gathers up the constituent signs governed by the codes of intrasignification so that they will be able to act as signifiers in the sign-functions governed by the codes of extrasignification – which specified them in the first place."*

The semiological language of the map makes epistemological, cultural, and political statements about the place represented. The cartographer's decisions on scale, framing, selection, and coding, are taken with a specific purpose or to make a statement. By marking boundaries, labelling cities, colouring rivers blue, or exaggerating the size of a particular island, the basis for the discourse of the map is established.

An awareness of the invisible codes of the map illuminates a reflection on the narrative and intention of a map. The following questions could be asked: What story does the map narrate? What has been included and what has been omitted, and why? What cultural or political interests might the map support? What proposed notions are being asserted as facts?

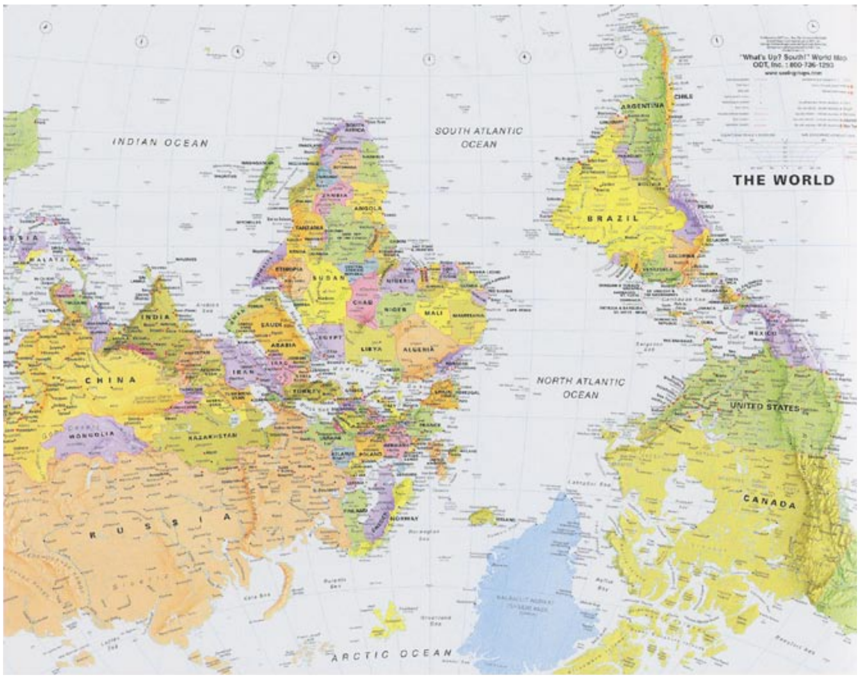
The following two maps (figure 3.8 and 3.9) can be taken as examples. The first is a mappamundi (i.e. world map) from the *Rudimentum Novitorum*, Lübeck 1475. The mappamundi shows the entire world as a circle with four quadrants: Europe, Africa, Asia, and Arabia. Jerusalem (as the centre of the Christian world) is positioned in the middle, with regions shown as hills which spread out towards the perimeter. This map may look "unrealistic" to modern eyes as cartographic sign systems (that we take for granted when reading a modern map) are not used. The most obvious omission is the lack of a latitude-longitude coordinate system to grid the locations in space. This map, while it wouldn't help to navigate around the world, nonetheless tells a story. By choosing what is represented (and what is omitted), and how, this map gives insight into the medieval Christian global perspective.



3.8 Mappamundi from the *Rudimentum Novitorum*, Lübeck 1475
image source:
Wood 1992, 68

The second figure is an upside-down world map (Harmon 2004, 132). This map, which is made with a grid system and uses a similar mapping technique to modern world maps, nonetheless appears strange to our eyes. It keeps with every cartographic code except one: the map places north to the bottom. This is disorienting and a map reader would likely have to flip the image upside-down to make sense of the geographic relations. Both the mappamundi and the upside-down map, by not adhering to cartographic tradition, emphasize the extent to which maps make use of a universally accepted visual language and code. On a well-designed map, in fact, these codes become invisible and disappear into the background, bringing the information of the map to the forefront.

Cartographers have, over the last centuries, developed a semiological language which has been to a large extent standardized. The ubiquity of the same code systems in maps gives them their power: they are "universally" readable (within a cultural context), and they pretend to offer a neutral view of the space as the language disappears into the background.



3.9 Upside-down world map.
image source:
Harmon 2004, 132

The underlying codes and messages (i.e. language) of maps have been presented to emphasize the challenges, risks and responsibilities of knowledge visualization. There is no "truth" or "neutrality" in visualization, but in the translation from the semantic space to the visual domain there must be decisions, measurements, and assertions made. Mapping knowledge is not an objective representation, but is the structuring, classification, codification, objectification, manipulation, and filtration of knowledge. Knowledge visualization is a reduction and an abstraction, squeezing a many-dimensional space of relations into a limited set of categorical relationships.

3.2.3 Mapping in the Digital Medium

Acknowledging the semiological, epistemological, and technological constraints of the representation of knowledge, knowledge maps can nonetheless be very useful devices. Information graphics, such as statistical charts or the peculiar examples analyzed in Edward Tufte's books (Tufte 1983; 1990; 1997), have proven equally useful (when well-designed) in communicating a particular perspective on a given set of information. But the challenges posed by the advent of digital technologies require the development of a new visual and interactive language that operates within a dynamic medium.

The digital medium introduces elements that cartographers have not previously had to consider in designing purely graphic spatial representations. These include:

- *visual dynamicism*, animated and updated in real-time to data changes
- *multimedia*, the integration of text and image with animation, video, and audio
- *interactivity*, the opportunity for the user participate in the creation of the map by changing it
- *networked distribution and data gathering*
- *3D and virtual environments*

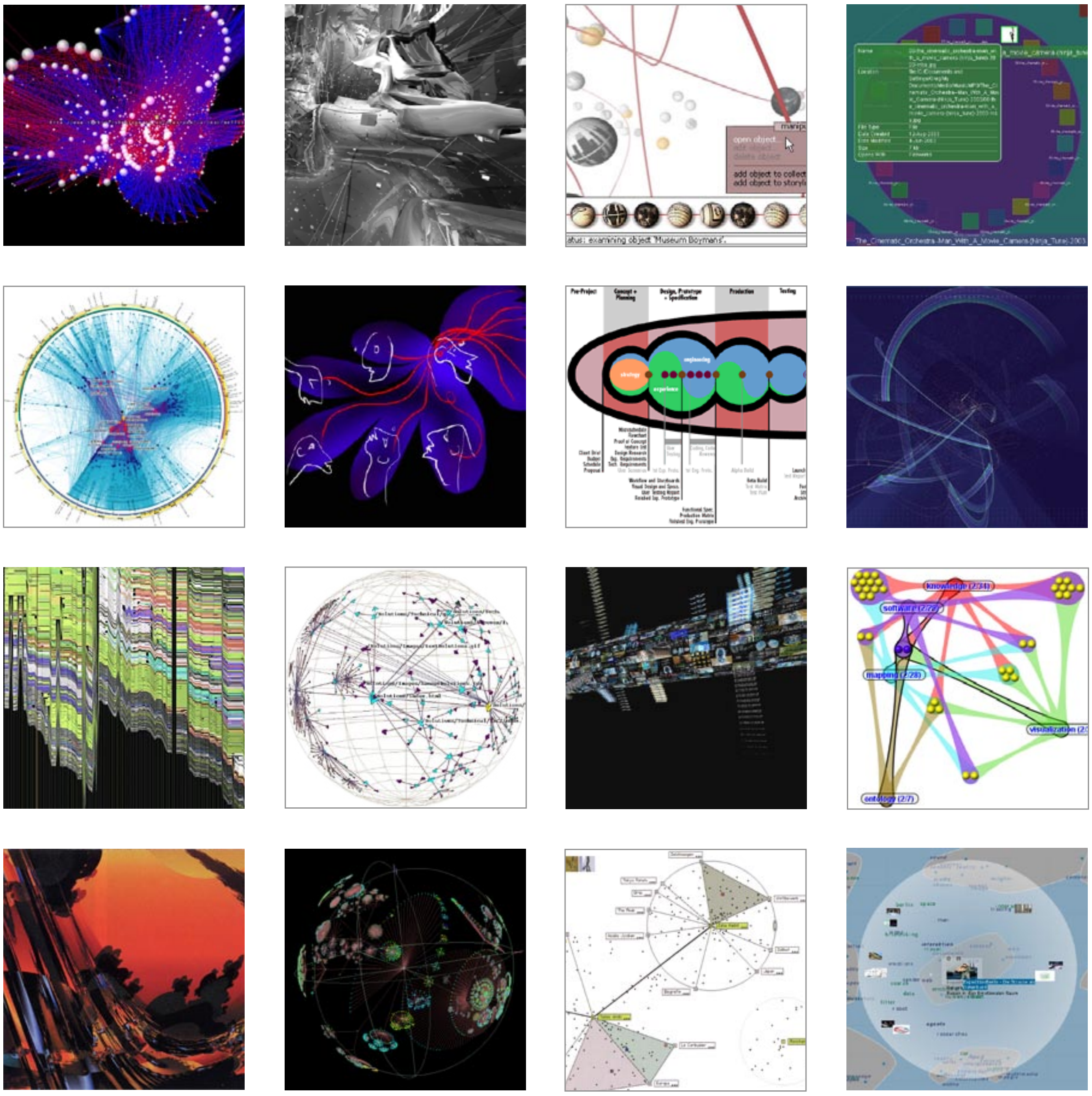
The degree of complexity of what and how the representation is achieved is substantially greater than with static maps.

Besides revolutionizing the cartographic interface, the possibility for user interaction gives the user a role in determining the form, scale, framing, labelling, and level of detail of the map. This transfer of power has been called a "democratisation" of cartography (Morrison, cited in Kraak 2001, 11), as decisions that traditionally fixed the layout of the map are now deferred to the user to suit his/her needs. The democratising potential of digital media is not unique to mapping but rather a general trend of the medium; similar power shifts are happening in other areas, such as journalism due to blogs (Stodiek 2004). Maps become more than a unidirectional communication tool; users a given a voice in their opportunity to engage, interpret, and participate.

The unprecedented dimensions of this dialogue of participation between map-maker and user (and among users) bring new dimensions into the design process. From a semiological perspective, the ten cartographic codes (figure 3.7) still apply, but must be refined to account for user interaction and visual dynamicism.

The creation of a language of digital knowledge visualization is in its early stages of evolution. This semiological system would have to account for both the symbolic representation of abstract information and the narrative of interaction with the system. Future developments will require epistemological research (organization and abstraction of knowledge), design research (representation and interaction), and technological research (reduction of technological constraints, such as speed, resolution, and memory). The ideal knowledge visualization will make use of a commonly accepted semiology of representation (inheriting much from cartography and information graphics) and interaction such that, like with modern maps, the interface "disappears" and purports to objectivity. With advances in knowledge representation, interface design, and information architecture, we may see knowledge maps that are as effective in navigating knowledge as our cartographic maps are in navigating landscape.

4 Survey of the State-of-the-Art in Information Visualization



This section contains a survey of the state-of-the-art in information visualization. Examples of visualization systems have been compiled from commercial applications, scientific research and artistic experimentation. The examples show a selection of unique approaches and illustrate part of the immense range of design possibilities. Images from each example are included along with a brief explanation (and in some cases analysis) of visual parameters and interaction schema. The texts accompanying each example are intended to summarize the properties of each system but are not linked to a grounding theory or argument. This more analytical perspective will emerge in the chapter following this survey.

4.1 A–P ***Images previous page:*** **A collage of screenshots from various projects discussed in this survey.**

Compiling a survey of visualization systems gathers a collection of application-specific techniques together to facilitate a comprehensive analysis. This can provide a starting point for the evolution of new ideas and a framework for the development of a coherent design theory. It can inspire design by providing examples of particular techniques put to work in particular applications.

Visualization design is dependent on the application of the system, the nature of the information, and the actions enabled for the user. Interfaces, which can be 2D or 3D and often represent several variables (time, size, distance, location, path, quantity, etc.) of information in one image, need to be optimized for certain users with certain needs. As such, the aspects of the information revealed and intended use of the system determine the graphic and interaction paradigm used. The designer is responsible for appropriately mapping data variables to graphic parameters using particular visual metaphors and establishing an interaction model to view and explore the image. The design process involves compromising certain functionality in order to enable others, and likewise systems tend to favour certain informational and operational structures.

The same application-specificity is inherent in traditional cartography. Making use of five main sign systems (fig. 3.6), the cartographer can show positions of discrete objects, mark boundaries, indicate continuums of equality and portray flow or movement. Each of these aspects relates to a distinct *meta-structure;* the guiding rules, relationships, or associations that govern a physical space. These meta-structures include paths, spatial relationships between objects, and movement of objects. An information space also has these elements (an architecture, semantic relations between objects, and changes in time) and, like cartography, requires different graphic and interactive techniques to represent each.

Inspired by the established cartographic distinctions, the survey was thus organized into three main sections which respectively describe three aspects of an information space which can be visually revealed: complex paths, relational content, and dynamic change. Respectively named *complexity*, *context*, and *dynamics*, these terms describe the most prominent meta-structures exposed by the visualization system (Long 1995, talks of a similar principle called "ultra-structures").

Complexity spaces, such as trees and hierarchies, show the topology or paths of an information architecture and are usually portrayed using images of networks with many nodes and links. *Context* spaces show the semantic relationships or content of information, and usually consist of objects spatially or visually arranged based on relative similarity or importance. *Dynamics* spaces, such as process diagrams or vector fields, show spatiotemporal changes and often engage a time axis or use arrows to indicate flow.

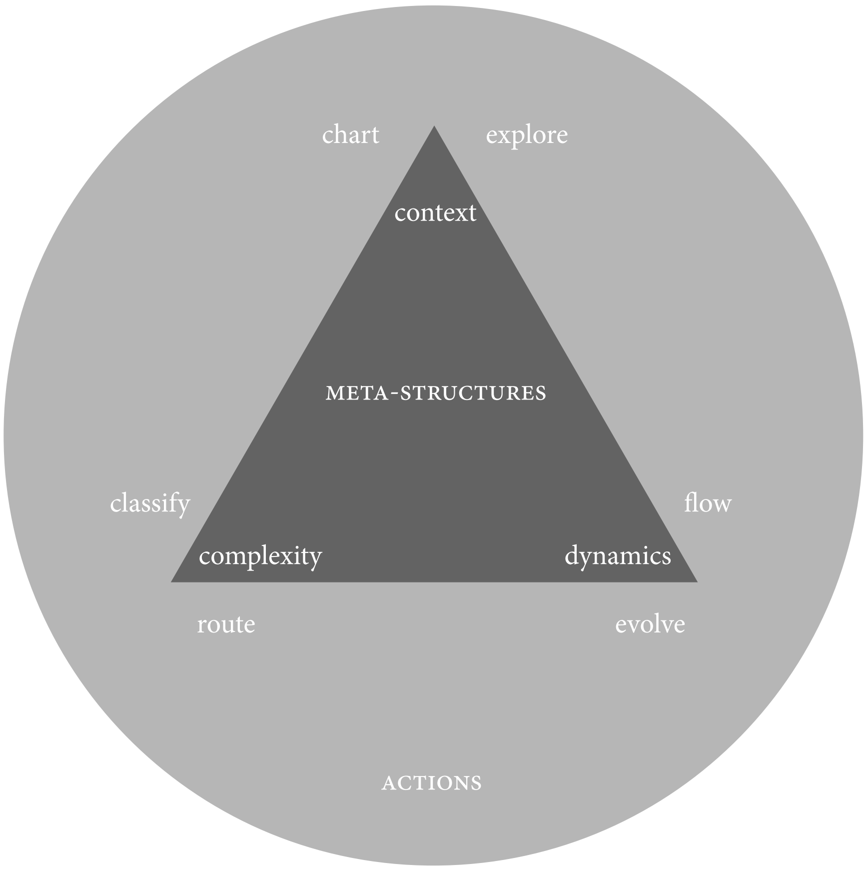
However, while most systems tend to dominantly display one or another of the three meta-structures (paths, relations, change), there is overlap. Categorization thus involves approximation, but is nonetheless useful to identify distinctions between techniques. General properties of each category are summarized by the following table.

4.2 Summary of the properties of each meta-structure as reflected in the organization of survey examples.

meta-structure	description	examples	dominant semiological elements	sub-sections
complexity	topology, paths	tree, hierarchy, network	illustration of nodes and links	classify, route
context	semantic relationships content	object clustering	illustration of similarity and difference	explore, chart
dynamics	movement spatiotemporal changes	process diagrams arrows and vector fields	temporal axis, illustration of flow	flow, evolve

Within each of these categories, systems tend to facilitate certain user actions. Accordingly, each meta-structure has been sub-divided (as indicated by the right column in the above table). The matrix of meta-structures and actions from which the survey examples were organized is mapped by the following figure.

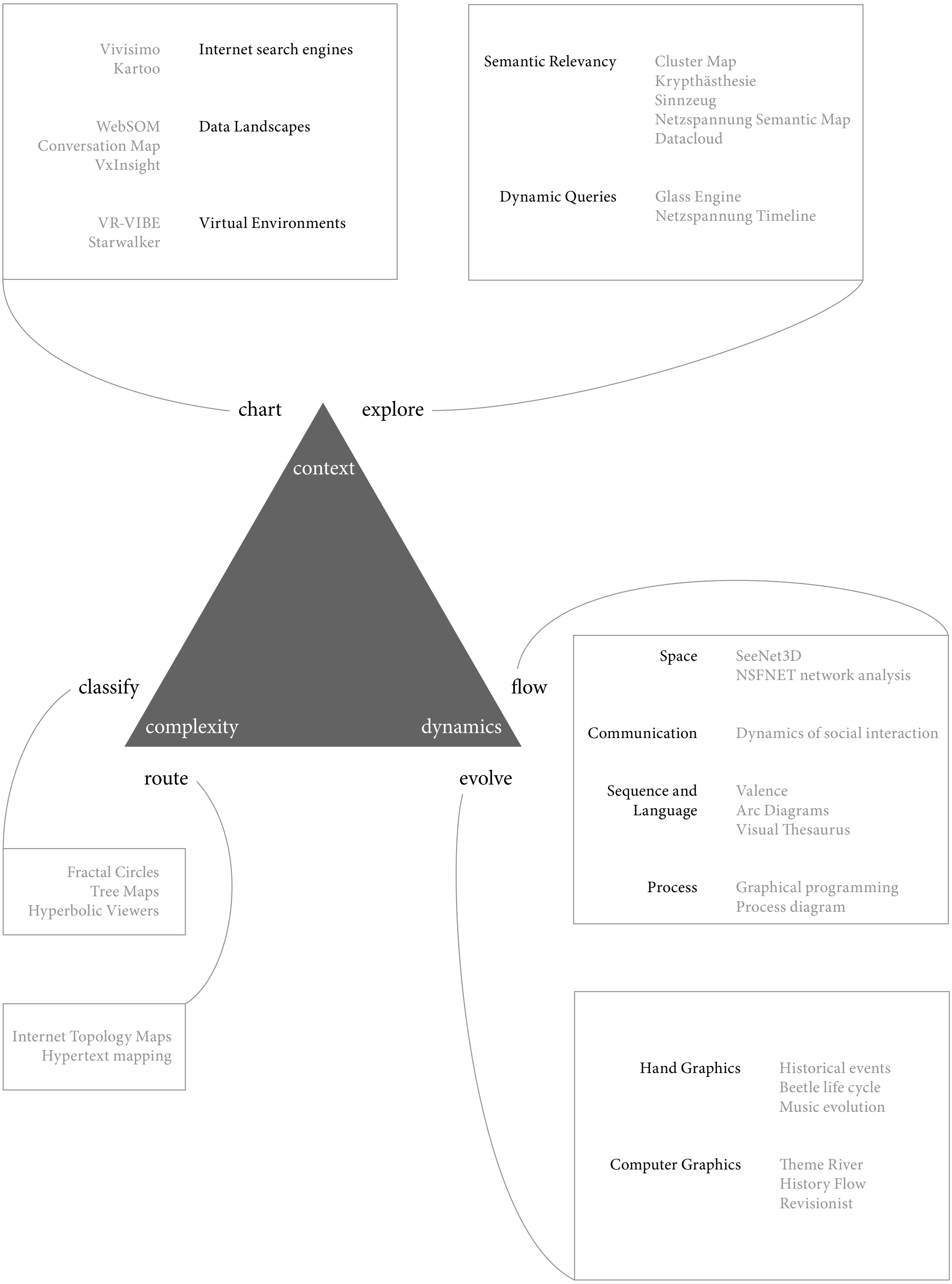
4.3 Matrix of the survey contents, in terms of meta-structures (inner triangle) and actions (outer circle). The two actions at each vertex of the triangle are the applications or actions associated with that particular meta-structure.



To summarize the contents of each section:

> *Complexity*: *classify* systems facilitate navigation through hierarchies, while *route* systems trace the topological structure of an information architecture. Topology refers to the locations and paths of data in the system; this includes file-folder hierarchies, the navigational possibilities to find to particular types of information, or the paths in between nodes in a large network.
>
> *Context*: both *explore* and *chart* systems illustrate semantic similarities and differences, but the former allows the user to interactively generate object clusters while the latter exposes relationships in static clusters. Semantics refers specifically to the essential meaning of a given piece of information; this can be described using meta-tags or an ontological system. *Explore* is subdivided into two sub-sections: *semantic relevancy* and *dynamic queries*. *Chart* is composed of three sub-sections: *internet search engines*, *data landscapes*, and *virtual environments*.
>
> *Dynamics*: *flow* systems are concerned with spatial, or temporal movement, while *evolve* systems focus on processes and changes to a system over time. *Flow* is sub-divided into four sub-sections: *space*, *communication*, *sequence and language*, and *process*. *Evolve* is composed of two sub-sections: *hand graphics* and *computer graphics*.

These distinctions should become apparent by the examples included in each section and are explained in more detail in the summary of techniques following the survey (section 5.2). To give a sense of the overall contents of this survey, following is a map of the contents of this survey.


Vivisimo
Kartoo
Internet search engines
WebSOM
Conversation Map
VxInsight
Data Landscapes
VR-VIBE
Starwalker
Virtual Environments
Semantic Relevancy
Cluster Map
Krypthästhesie
Sinnzeug
Netzspannung Semantic Map
Datacloud
Dynamic Queries
Glass Engine
Netzspannung Timeline
chart
explore
context
classify
complexity
dynamics
flow
route
evolve
Space
SeeNet3D
NSFNET network analysis
Communication
Dynamics of social interaction
Sequence and Language
Valence
Arc Diagrams
Visual Thesaurus
Process
Graphical programming
Process diagram
Fractal Circles
Tree Maps
Hyperbolic Viewers
Internet Topology Maps
Hypertext mapping
Hand Graphics
Historical events
Beetle life cycle
Music evolution
Computer Graphics
Theme River
History Flow
Revisionist

4.1 Visualizing Complexity

4.4 *Image previous page*: Summary of survey contents. Each box contains the sub-section names (in black) and the example names (in grey).

A major focus in information visualization research examines techniques and design metaphors for facilitating navigation or orientation within a complex topology of nodes. The challenge is to illustrate a large number of elements and how they are linked by an information architecture. Two particular applications include the facilitation of navigation through complex classification hierarchies and the tracing of complex paths between documents or network nodes. This section features examples of visualization techniques distributed into two categories as follows:

Classify - facilitating navigation through complex classification hierarchies

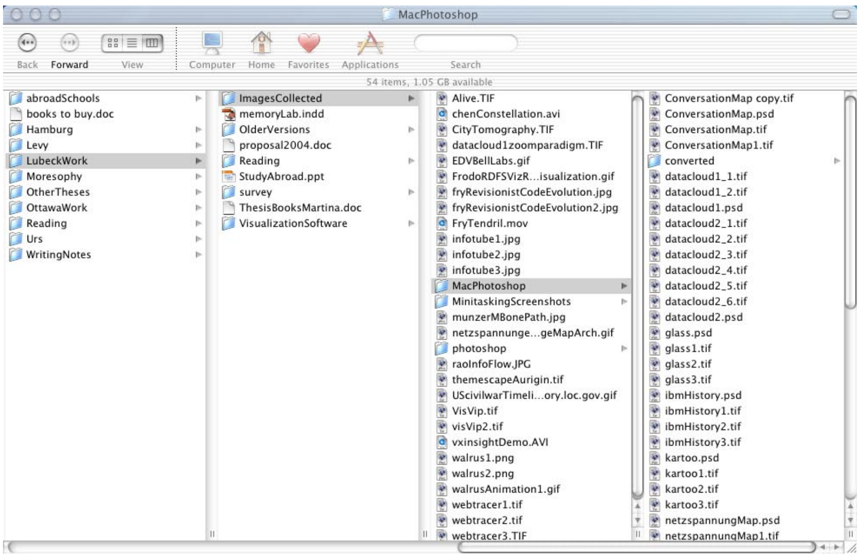
Route - tracing complex paths between network nodes

4.1.1 Classify

A common example of a complex information architecture is a hierarchy classification: a categorization of elements that branch off into subsequent sub-elements. The hierarchy, often referred to as a tree, consists of a topology of peripheral nodes which fan out from a central root.

User tasks when working with hierarchies can be diverse, and in assessing a hierarchy visualization it is useful to recognize which of the following questions are addressed (Card 1999, 630):

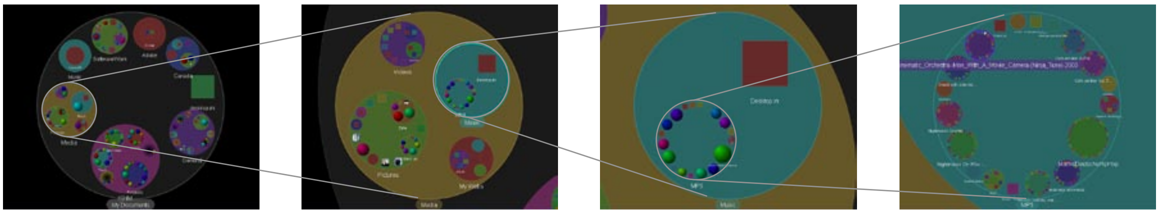
How many total nodes are in the hierarchical system?
How much do the nodes fan-out into sub-nodes?
How far is the deepest node from the root?
Which level has the most nodes?
What are the names of each node?
What are the attributes of each node?



4.5 This is the Macintosh OSx file explorer interface. How many of the above questions can be answered? Compare with the examples on the following pages.

Current operating systems (fig. 4.5) use textual paradigms for viewing the contents of file folders. Future interfaces will likely use a visual interface for finding and organizing files, in application of an information visualization technique known as *focus and context*. This refers to the simultaneous overview (context) of the entire information structure with a detailed view (focus) of a particular section. This technique is usually more effective than the *overview and detail* method in which users zoom for a detailed perspective and lose the overview (unless it is offered in a second window) (Card 1999, 634). A design mantra stated by a leading visualization research team is, "*overview first, zoom and filter, then details-on-demand*" (Card 1999, 625). *Focus and context* systems enable access to object details while maintaining the overall perspective, improving the user's orientation. Three approaches are presented which illustrate this principle by showing several (horizontal and vertical) layers of a hierarchy and exposing object details when requested.

Fractal Circles



4.6 The navigation of files and folders on a harddrive with Grokker. The grey lines indicate the circle that has been zoomed into.

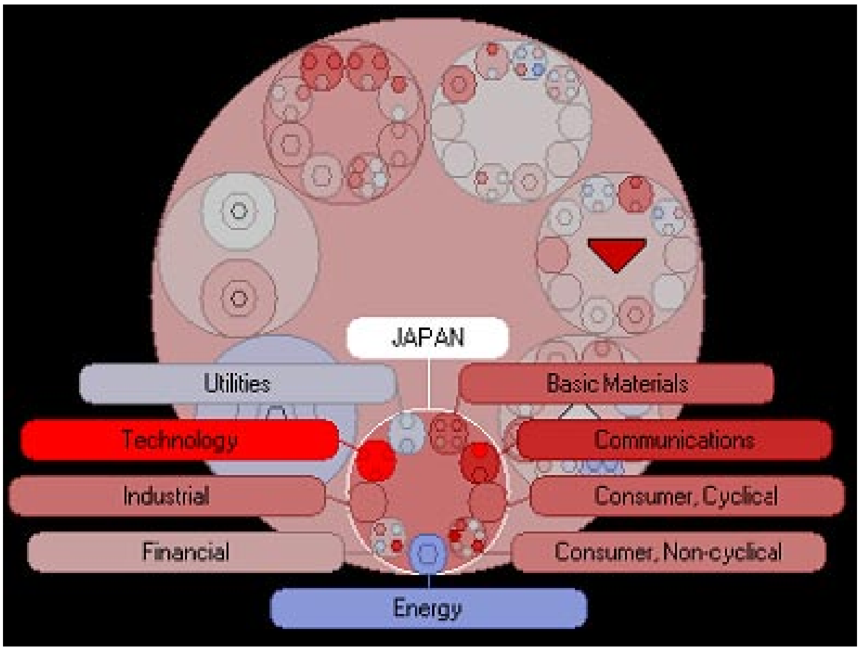
www.grokker.com

A hierarchy is composed of an iterated pattern of objects within objects within objects. This is the same structure of the mathematical concept of the fractal, a geometric pattern that repeats at different scales. The example (fig. 4.6) from the Grokker software company uses circles arranged within circles; colour coding allowing a rapid overview of the contents of each circle. At a single glance several sub-levels of the hierarchy system are visible (both vertically and horizontally). The number of circles refers to the number of sub-objects, and the colour is mapped to a parameter such as object size or file type. This system is particularly useful for financial analysis if colour or shade is related to the magnitude of profit or deficit, allowing elements of significant financial gain or loss to be quickly identified.

The fractal circle metaphor is also used in Fractal:Edge (fig. 4.7), a commercial application for the searching through large archives and financial data.

4.7 This screenshot from the Fractal:Edge website shows the result of a rollover onto the bottom circle, exposing object titles and inviting a click to zoom into a particular circle. Colour is mapped to financial gain or loss, and red circles immediately bring poor financial performers to attention.

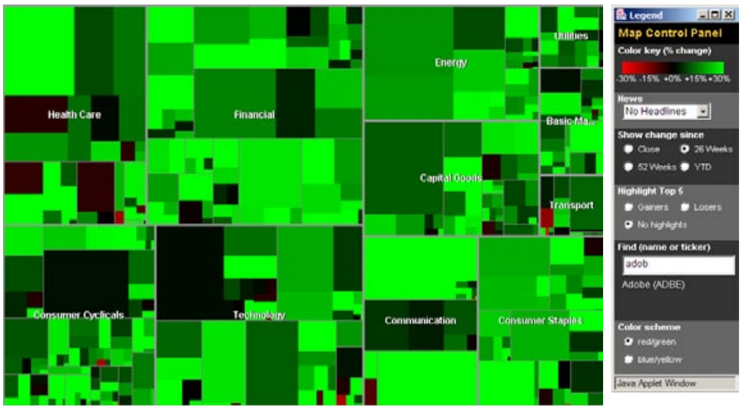
www.fractaledge.com



Tree Maps

An invention of Ben Shneiderman's prolific human-computer interaction lab at the University of Maryland (at *http://www.cs.umd.edu/hcil/research/visualization.shtml*), this system flattens node-link tree diagrams onto a 2D image of squares. Directory levels are contained in squares, with subdirectories iteratively contained therein. Square size maps to the size of the subdirectory, shading to directory depth (i.e. the darker the colour the deeper inside the tree) and colour can be mapped to file type. These graphs have been applied for statistical analysis (*www.cs.umd.edu/hcil/treemap-history*), and are useful for obtaining a rapid overview of a large data set.

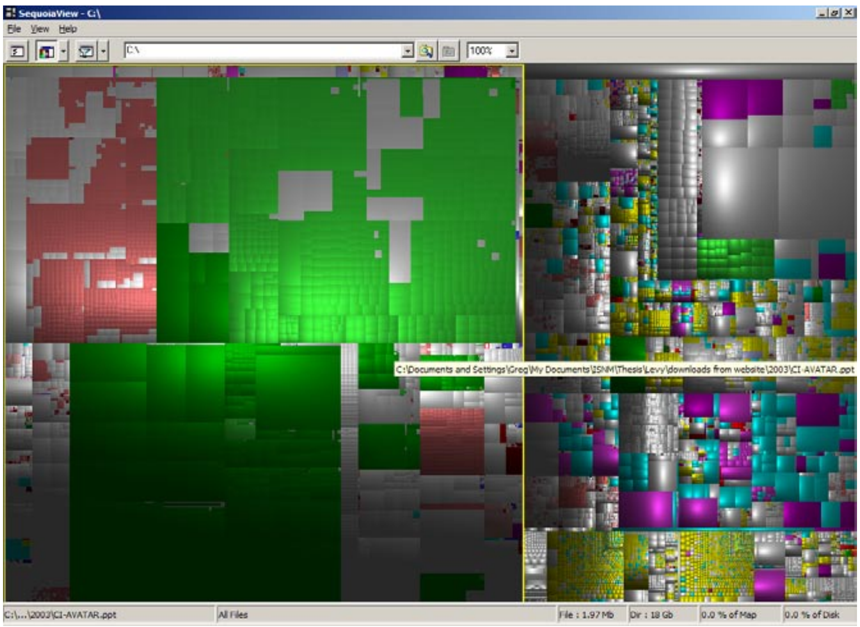
An elegant adaptation of the treemap is the Smartmoney Market Map (fig. 4.8), an online Java applet. Different market sectors are represented in different squares, filled with sub-squares of companies within that sector. Stock value determines the size of the company's square, and the colour is determined by the value change over a user-specified period of time. Green refers to an increase in value, and red refers to a decline. A rollover gives details of the square, including company name and some statistical parameters. This model provides an overview of the day's market performance at a glance (i.e. if the map is mostly red, market values have dropped; if the map is mostly green, values have risen). The user is given access to market performance more profoundly in one image than with would be possible with many traditional bar and line graphs.



4.8 Smartmoney's Market Map shows mostly green, indicating a mostly profitable session on the stock exchange. The control panel on the right allows the user to toggle view parameters.

www.smartmoney.com/marketmap

Another application is Eindhoven Technical University's Sequoia View software (fig. 4.9). This free download is a program that scans a user's hard drive and displays the directory structure in an attractive treemap. The algorithm used to generate the squares uses a gradient instead of a line to separate squares, making more efficient use of valuable on-screen pixels. This program can be used to quickly find the larger files stored on a hard drive and to navigate the contents of all folders in one interface. A drawback of this interface, however, is that the display favours large files, and small text documents show as just a few pixels or less.

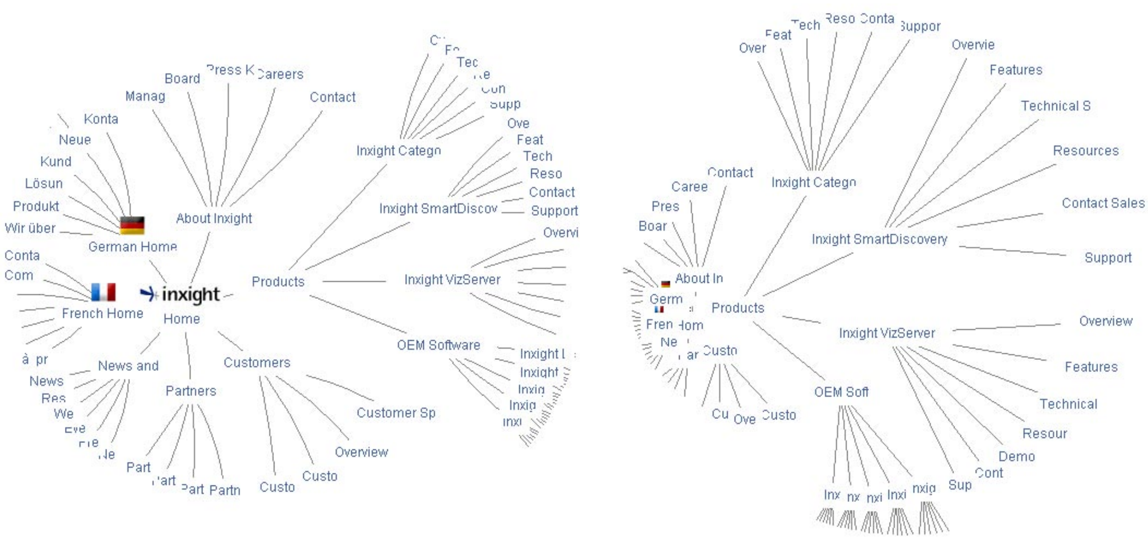


4.9 Sequoia View's image of a hard drive contents. The large squares in the top right corner show a group of large files, probably video media. The horizontal yellow window across the centre shows the file name after a rollover.

www.win.tue.nl/sequoiaview

Hyperbolic Viewers

The use of hyperbolic geometry (as opposed to Euclidean) is an application of the focus and context technique, producing a fisheye-lens view of a hierarchy tree. This allows users to view an entire tree and the details of a certain area simultaneously (Lamping 1995, 382). Hyperbolic space expands exponentially (as do hierarchy trees, making it a good mathematical solution to this particular visualization problem), with screen space distributed more at the focused area of the tree and less at other sections. The user can drag the focal point with the mouse, thus obtaining a magnified view of any section of the tree, while the rest of the nodes are shrunk into the sides of the map. The interactivity in this model is particularly elegant, with quick searches through large trees facilitated by intuitive dragging and smooth animation. A drawback to this technique, as with many of the strategies for visualizing complexity, is that topological path information between nodes is displayed but semantic relationships are neglected. Three examples are featured which use hyperbolic geometry.

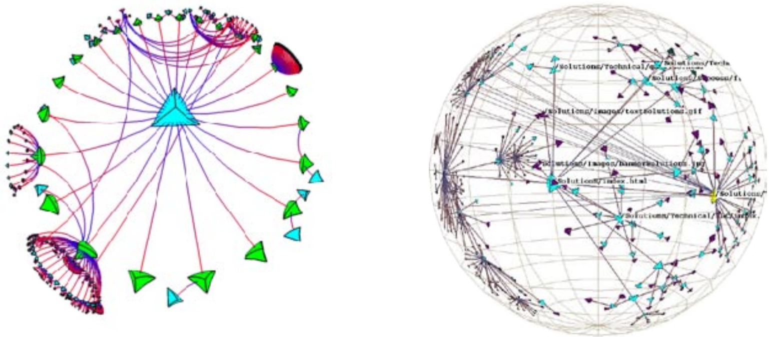


4.10 A–B Inxight Star Tree sitemap navigator. The image on the right shows the tree dragged to the left, compressing the left half of the tree into the bottom left corner (notice the tiny French and German flags).

www.inxight.com/map

The Inxight Star Tree sitemap navigator (fig. 4.10) was developed from original research at the Xerox PARC Lab (Lamping 1995, 382). It is a 2D technique for exploring the site architecture of a large website. The page titles are only fully visible near the centre of the tree, while only tiny lines show for the nodes in the compressed edges.

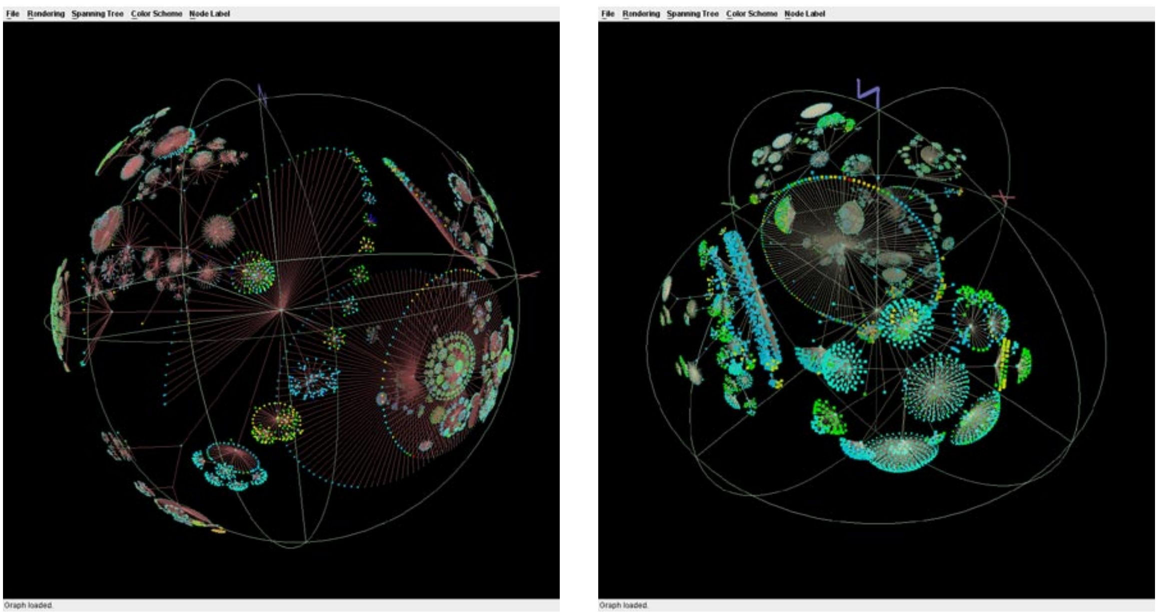
Tamara Munzer's 3D hyperbolic quasi-hierarchical graphs (fig. 4.11) use the third dimension to increase the size of the trees that can be visualized. The image on the left shows the "*conformal model of hyperbolic space, which preserves angles but maps straight lines to circular arcs*" (Munzner 2001, sec. 3.2.2.2). The image on the right, visualizing a website of about 5000 nodes, uses the "*projective model of hyperbolic space, which keeps lines straight but distorts angles*" (Munzner 2001, sec. 3.2.2.2). Colour coding is used to distinguish file types and the selected (in-focus) node. Notice that the links overlap and become difficult to track to their destination nodes. An improved use of colour and shading could augment the readability of the in-focus node area. There are cognitive limitations to the size of trees that can be visualized due visual clutter and occlusion; this makes it difficult to use this technique to graph an enormous tree like the entire internet which contains billions of nodes (Munzner 2001, sec. 3.7.2).



4.11 A–B Tamara Munzer's 3D hyperbolic graphs. The conformal model is applied in the image the left and the projective model is used on the right.

graphics.stanford.edu/papers/munzner_thesis

CAIDA, the Cooperative Association for Internet Data Analysis, has applied Munzner's research to the development of the Walrus Visualization Tool (fig. 4.12). The design has reduced some of the visual clutter of Munzner's original version by diminishing the boldness of lines and node point boxes. The aesthetics and readability of these graphs are an improvement over the Munzner example, facilitating visualizations of larger trees.



4.12 CAIDA's Walrus visualization tool, based on Munzner's 3D hyperbolic geometry.

www.caida.org/tools/visualization/walrus

4.1.2 Route

Internet Topology Maps

The internet's vast global network of connected computers is arranged in a complex web of linked servers. Several projects are underway to archive and visualize the topological routes of network server connections on the core of the internet. These graphs can be used to analyze data paths and diagnose network problems, and can be animated to track the evolution of a network over time (Cheswick 2000). These maps are purely topological and do not illustrate semantic relationships between nodes; this is a necessary compromise to achieve a detailed graph of 100,000 nodes or more.

4.13 Original sketch of ArpaNet network with 4 total nodes in December, 1969

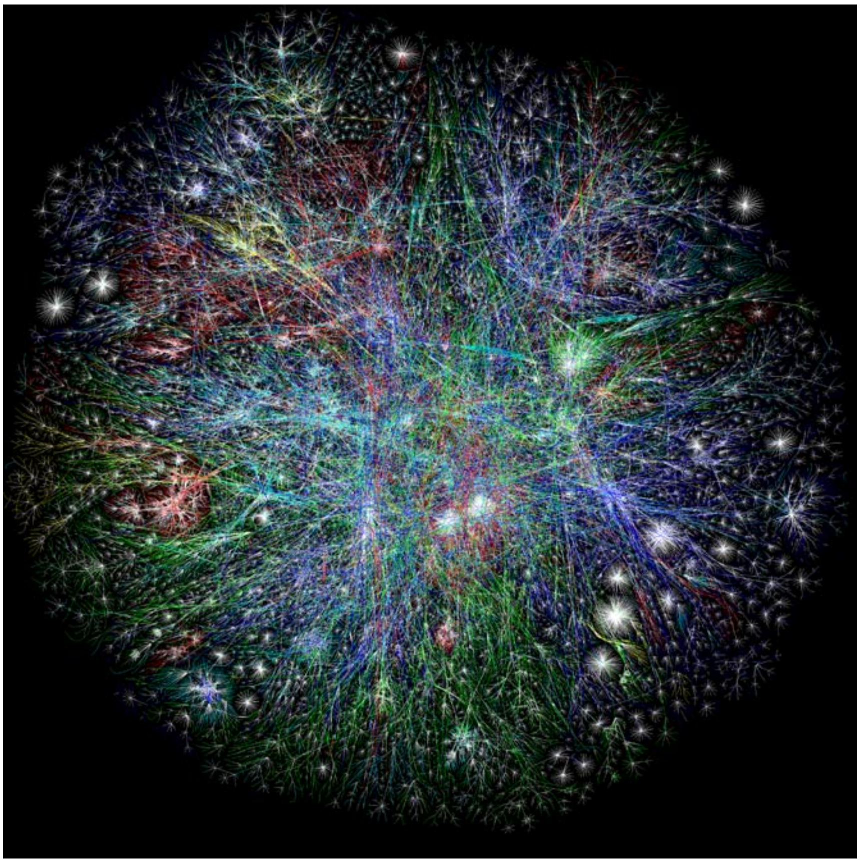
source: *www.xtrj.org/images/1969_4-node_map.gif*

The first example is a sketch (fig. 4.13) by an ArpaNet engineer from December 1969, showing the structure of the first long-distance computer network. Only four nodes comprised the network, with computers being located at universities in California (Los Angeles, Santa Barbara, Stanford) and Utah. The simplicity of this diagram contrasts starkly with the next two examples.

The map below (fig. 4.14) was produced by the Opte Project in November 2003. The Opte map uses colour coding by geographic location (of web

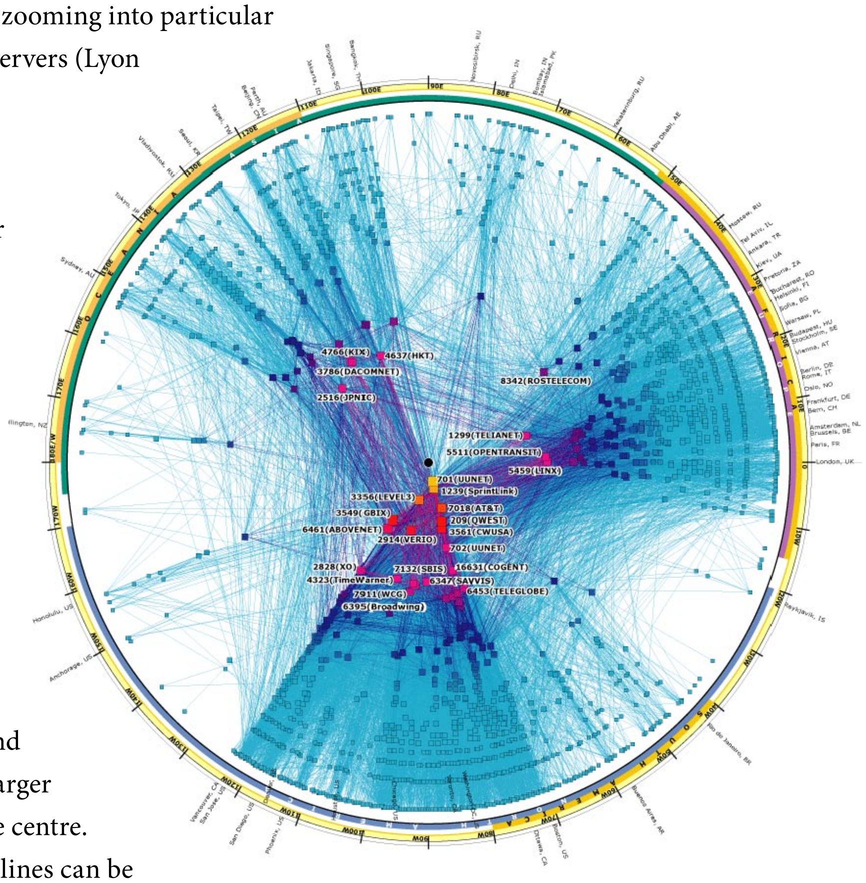
4.14 Opte Project internet map

www.opte.org/maps



server IP addresses) and shows over 5 million edges (node connection paths). A desktop computer takes several hours to generate the image from an algorithm which uses simple rules of attraction and repulsion to spread the nodes into a legible distribution (Dodge 2001b, 42). Another map of this style has been produced by Lumeta Corporation's Internet Mapping Project (*www.lumeta.com/mapping.html*). These topographical maps are static images, but as computing power increases they will become animated and interactive and allow zooming into particular network sections or web servers (Lyon 2003).

A completely different visualization from similar data has been produced by CAIDA to map the internet core (fig. 4.15). Over a million ISP (internet service provider) IP (internet protocol address) nodes and over 2.5 million links are shown on this "Skitter" map. The map uses polar coordinates, charting geographic location around the circle perimeter and larger ISP providers closer to the centre. The density of blue radial lines can be seen to be greatest along three axes, showing the concentration of web core service in America, Europe and Asia.



4.15 CAIDA Skitter AS internet graph, May 2003

www.caida.org/analysis/topology/as_core_network

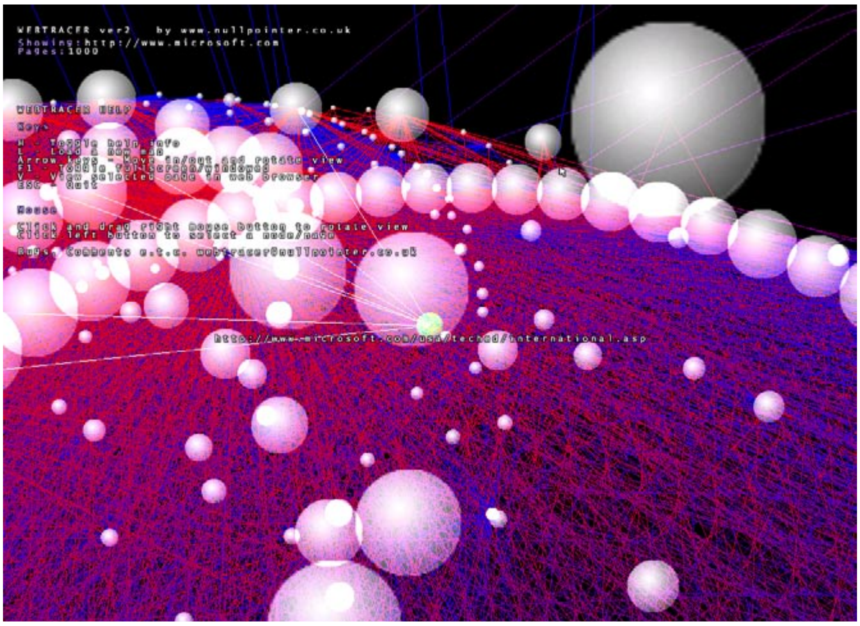
Hypertext mapping

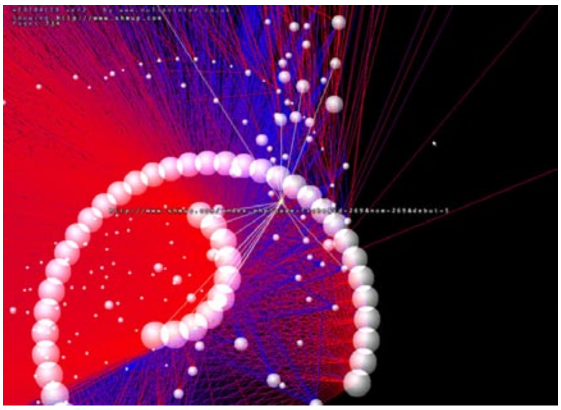
Hypertext maps visualize hypertext geography, the paths between hyperlinked webpages on an internet site. In large websites the overlapping links facilitate many different paths through the site; the actual path taken depends on what information the user desires. This complexity produces an awkward system to visualize due to the density of criss-crossing lines, occlusion, and readability.

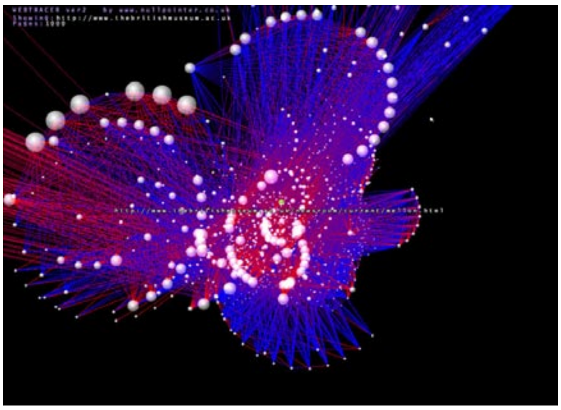
A project that visualizes hypertext structures of websites is a free downloadable software called WebTracer (fig. 4.16). The software consists of two parts; a "spider" which traces a website's links, and a "visualizer" which produces from this data 3D molecular visualizations. The striking images portray the molecular metaphor, showing pages as atoms and links as lines. Further information about nodes can be obtained by clicking on them, and the entire visualization can be explored and rotated in 3D. The images, by emphasizing link density, illustrate the promotion or demotion of certain information in a website (Woolman 2002, 48).

4.16 A-C Screenshots from Nullpointer's WebTracer software. The top-left image is a map of *www.shmup.com* (734 pages), the top-right is a map of *www.thebritishmuseum.ac.uk* (1000 pages), and the bottom is a map of *www.microsoft.com* (1000 pages).

www.nullpointer.co.uk/-/webtracer2.htm







4.2 Visualizing Context

Contemporary information interfaces, especially text-based keyword searches, provide extensive results but offer little insight into the semantic relationships between digital objects. To exemplify this shortcoming, we can observe the search results given by popular search engines such as Google (*www.google.com*) or Yahoo (*www.yahoo.com*). These engines are able to find thousands of relevant documents based on a given set of keywords, but they are presented one-dimensionally such that no inter-relationships or classification of the results are given. An improvement would be to organize the documents returned by the search into categories (based on a given ontological structure), allowing the user to contextualize more broadly the accessible data. Some search engines (*www.altavista.com*, *www.vivisimo.com*) are beginning to implement a categorization of results displayed as a supplementary list beside the main listings. The semantic groupings, however, are produced by automated text analysis and often miss subtle semantic nuances.

Research for the next generation internet (i.e. semantic web) is concerned with building a theoretical and technological infrastructure to support an extensive ontological structuring of web data. Once these organizational information layers are in place, it will be possible to discover and map contextual relationships between digital objects in an interactive visualization, producing a comprehensive overview of the semantic content. This section features examples of interfaces which visualize contextual relationships.

The projects have been organized into two sections:

> *Explore* - interfaces with dynamic interactivity, allowing exploratory manipulation of the visualization. The sub-sections are *semantic relevancy* and *dynamic queries*.
>
> *Chart* - representing an information space with static (navigable) maps. The sub-sections are *internet search engines*, *data landscapes*, and *virtual environments*.

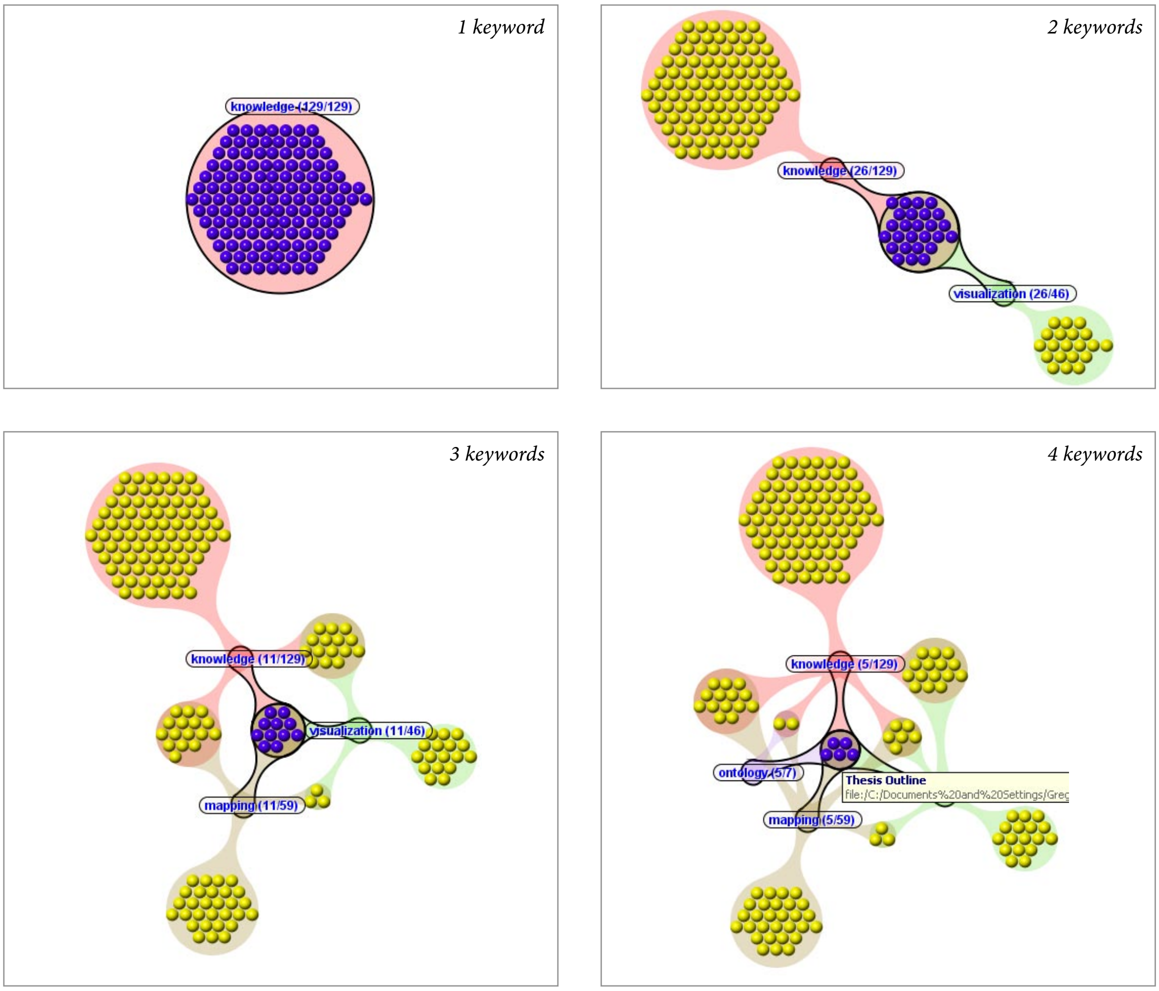
4.2.1 Explore

This section presents two types of visualizations; representations based on semantic relevancy and dynamic queries. Within each of those categories are several examples.

Semantic Relevancy

Cluster Map

A problem with the organization of objects of an archive into an ontological hierarchy is that particular objects often belong to multiple classes. An excellent tool for visualizing these overlapping ontological spaces within an archive is AutoFocus Personal (fig. 4.17), marketed by the software company Aduna. The software, available as a trial download from *www.aduna.biz*, uses a technique called a "cluster map"; documents are represented by coloured circles and grouped into a larger shaded circle

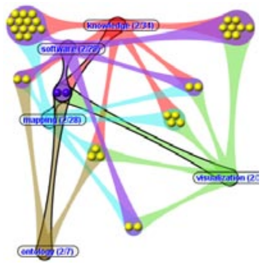


4.17 A-D Cluster maps for searches of 1-4 keywords. These screenshots are from searches for files on a hard drive. The software is called *AutoFocus Personal*.

www.aduna.biz

(or "clusters") with other objects fitting the same descriptive keyword. If a second keyword is entered by the user, the map animates into a new configuration which illustrates which class the objects belong to (one or both) by drawing a second and third circle representing the new keyword and the overlap of both. The visualization becomes more complex as further keywords are entered and the objects are sorted into multiple class clusters. Coloured shading aids the visual process of tracking the classes that clusters belong to. This technique is very useful for organizing and locating particular objects and can effectively illustrate up to five or ten classes (fig. 4.18), but the graph becomes complex and difficult to read with many more ontological classes represented. A more extensive discussion and analysis of this system (and similar ones) is published in Chaomei Chen's *Visualizing the Semantic Web* (Chen 2003b, 36).

4.18 The web of overlapping clusters becomes difficult to read with 5 keywords in the search. Colour-coding helps to track which clusters relate, as the user can visually connect the cluster to the search words by following the coloured lines.

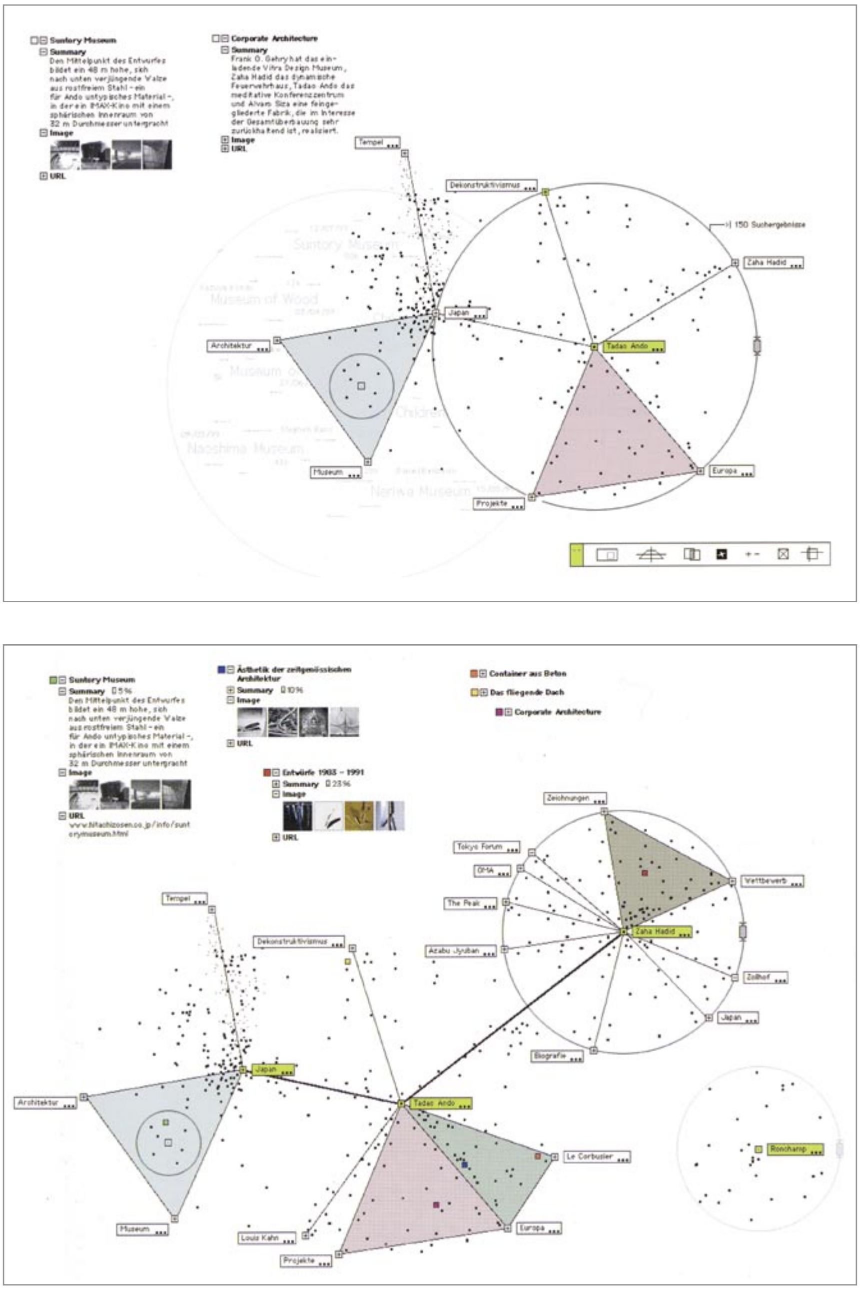


Krypthästhesie

Developed by Projekttriangle (*www.projekttriangle.com*), Krypthästhesie (fig. 4.19) is a search and explore interface for a semantically organized archive or the semantic web. The software is not functional but is developed as a prototype concept. The interface uses clustered black pixels, or "dataclouds" (Fawcett-Tang 2002, 69), to represent semantically related objects in the database. Search terms are typed directly into the visualization and are geometrically aligned (in triangles or circles); once words are entered pixels are animated to be magnetically attracted or repelled. A circle surrounds the central search term, and around the perimeter of the circle further search terms can be entered which shift the positioning of the pixels according to semantic relevance. Further search terms can be drawn around the circle, forming a configuration of triangles and circles which can be zoomed into for a closer view of object details. The overall context remains as the full datacloud view is still visible when zoomed in, faded and translucent in the background. A click on a pixel shows a summary of the document, related images, and a link to the website. Image searches can be performed in which the pixels are replaced by tiny image thumbnails which also form zoomable data clouds.

4.19 A–B **Projekttriangle's Krypthästhesie. This project is described in an online video at *netzspannung.org/ workshops/online-archives* (panel 2, item 7).**

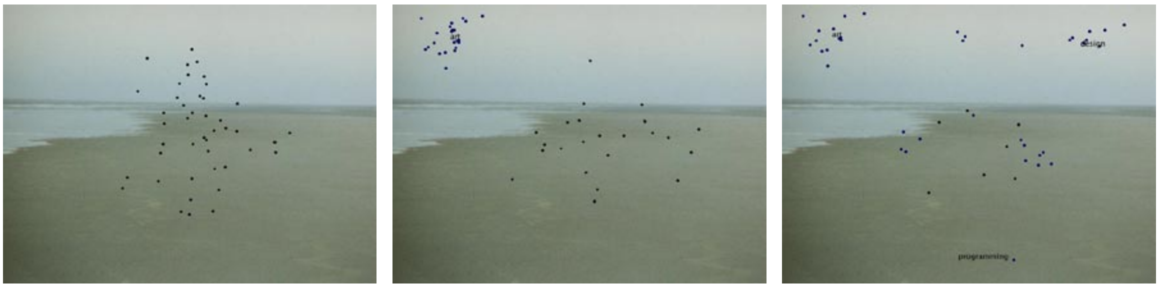
***image source*: Fawcett-Tang, page 69**



This interface uses a metaphor of magnetized particles projected on a flat map. The model uses an intuitive interaction schema; the animated attraction and repulsion of pixel clusters is a useful technique for visual searches and can be implemented once internet documents are semantically classified. An application for research is an extension of this model into a 3D virtual environment (similarly to the V2 Datacloud2 project below).

Sinnzeug

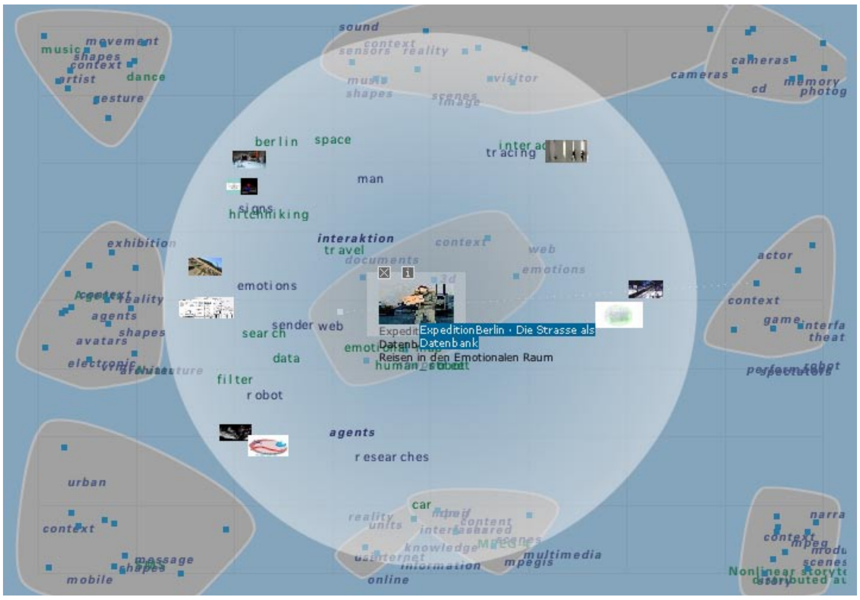
A similar if less sophisticated system to Krypthästhesie is currently online. Called Sinnzeug (*www.sinnzeug.de,* fig. 4.20), this Macromedia Director Shockwave (*www.macromedia.com/software/shockwaveplayer*) program uses the magnetic datacloud model for a search engine interface to a small selection of about 25 websites. Each website is represented by a small black circle distributed on a flat image. Keywords can be entered on the screen and attract or repel the dots based on the semantic content of the associated websites. If keywords are dragged around the window, the positioning of the dots is redistributed. The link database is small and refers specifically to art or design websites, as such a selection of 5 hint-keywords (such as *programming*, *art*, or *concept*) appear after a click. A roll-over onto a dot produces a site icon, a short description, and the web address. A mouse-click opens the website in another browser window. All dots clicked on are connected by a thin blue line, allowing the user to see the exploration history through the cloud.



4.20 A-C Sinnzeug screenshots. The image on the left shows the initial random distribution of objects. The middle image shows objects clustered around one keyword in the top right corner. The image on the right shows three keywords and the resultant clustering of objects. The cluster in the middle contains objects that do not relate to any of the keywords.

Netzspannung Semantic Map

This project is one of the *Knowledge Discovery* tools at the Netzspannung website (*netzspannung.org/tools/knowledge-discovery*), a knowledge portal for digital arts hosted by the MARS Exploratory Media Lab (*mars.imk.fraunhofer.de*). The semantic map (fig. 4.21) is an online shockwave interface to an archive of projects featured at a conference hosted by the MARS lab. Conference papers are assigned semantic concept tags based on text analysis and spatially arranged based on a self-organizing Kohonen neural net algorithm (*netzspannung.org/netzkollektor/output/tool.xml?entryId=36654&section=base&lang=en*). The projects with the most keyword tags in common are organized into clusters, arranged into a 2D spread of blue dots. On a rollover, all projects with the same keyword tag are highlighted, and on a click all of these dots are enlarged and pulled into focus in the centre of the map. The clicked object is placed in the centre and can be clicked on to obtain more detail or be linked to its web page. All objects clicked on are subsequently connected by a thin line, visualizing the path of user movement through the archive.



4.21 A-D Netzspannung's Semantic Map. The top-left image shows the initial interface. Clicking a keyword highlights all other objects that are assigned the same keyword and shows whether the keyword was automatically or human generated, as in the image on the top-right. The middle shows the result of a click on an object, drawing all similar objects towards the centre. The bottom shows the detail-view accessible by rolling over the *info* icon.

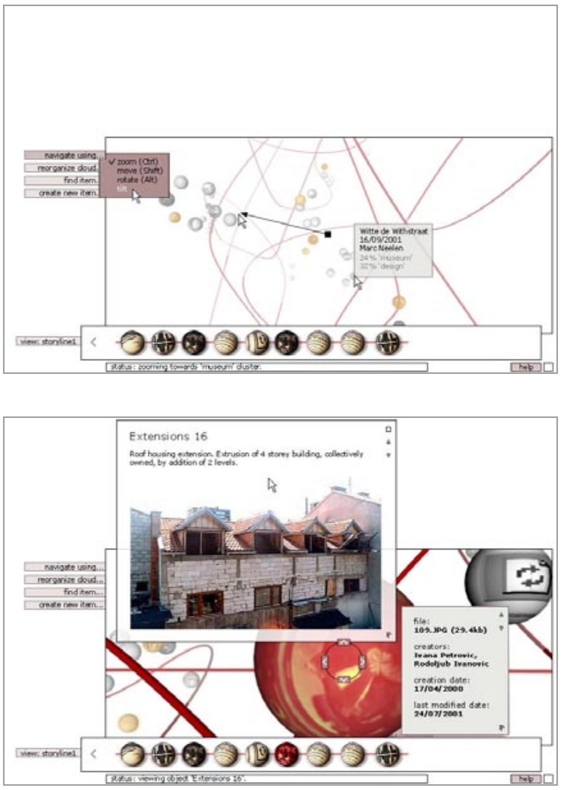
netzspannung.org/tools/knowledge-discovery

Datacloud

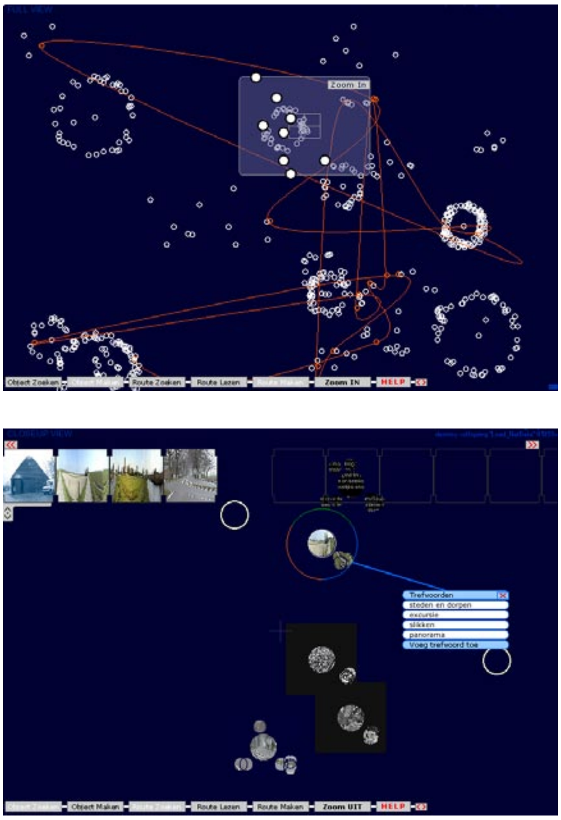
The Rotterdam-based media research lab V2 has developed two versions of a visual exploratory archive interface called Datacloud. Datacloud2 (fig. 4.22) is a 3D navigable virtual environment in which each media object from a multimedia archive is represented by spheres. The spheres are arranged by semantic association into constellations (a 3D cluster), spatializing the environment as a metaphor to a conceptual mind map of human cognitive associations. Each 3D sphere is textured with an image from the media object it represents, and navigation towards a sphere exposes object details. The user's navigation history is shown as a "storyline" of connected balls along the bottom of the screen. Datacloud2 is a Java applet that is available online as a demo at the project website.

Datacloud1 (fig. 4.23) is the first version of V2's online interfaces to multimedia archives, this time in 2D and programmed in Shockwave. As with previous examples the interface uses the clustering model, but what is unique is the paradigm used to obtain detail about the individual objects. The user can scan over the clustered dots with a sort of translucent magnifying frame which enlarges the dots to be clicked on. This use of translucency to show both the overview (context) layer and the detail (focus) layer simultaneously is an effective paradigm for the *focus and context* visualization model. After being clicked on, an option menu appears which reveals choices for different types of details about the object. The view can be zoomed into to show a small region of the cluster, enabling fine navigation of the media (text, images) related to the object.

Several more examples of experimental visual interfaces to large archives are available at the Rhizome net art website (*rhizome.org/interface*).



4.22 A-B **DataCloud2**
datacloud2.v2.nl



4.23 A-B **DataCloud1**
www.dwhw.nl

Dynamic Queries

Dynamic queries are visual database interfaces which integrate graphic parameter input controls and a real-time visualization of the search results (Card 1999, 236). Useful applications include the *Dynamic Home Finder* (Shneiderman 1994) or other GIS systems where geographic data is visualized directly onto a map to show the user instant results to an adjustable search query. This technique is effective because of the possibility to explore the archive by direct interaction with the visualization. Two examples based loosely on this technique are illustrated; the Glass Engine and the Netzspannung Timeline.

Glass Engine

This IBM research project is located on composer Phillip Glass's website (*www.philipglass.com*). It is a graphical interface (fig. 4.24) to an audio archive of Glass's compositions. The interface is composed of eight draggable bars: three on top for the albums sorted by title, date, and time length; and five on the bottom where each piece is rated for joy, sorrow, intensity, density, and velocity. On each of the eight bars is a row of notches representing the tracks ordered from first to last according to the parameter of the bar (i.e. for the title bar, the first notches are albums beginning with 'A' and the last notches are titles beginning with "Z"). The range of included notches on the bar can be filtered by dragging the ends of the bar towards the centre, such that only tracks beginning with a particular letter will show notches. All of the bars can be dragged to play the track located at the notch that is aligned in the centre of the

4.24 Glass engine
www.philipglass.com/glassengine

window with a thin white line. As one bar is dragged, all seven other bars move simultaneously to align with the notch from the selected track. Favourite tracks or albums can be tagged with a tiny white line to facilitate the finding of particular tracks. The simplicity and intuitiveness of this interface is astounding, as is the ability to explore the entire Glass repertoire with eight parameters visualized in real-time to describe the selected piece. This superb example fulfils Edward Tufte's guidelines for graphical excellence: "data density" (Tufte 1983, 167) and "clear portrayal of complexity" (Tufte 1983, 191); the interface compresses dense information retrieval into a minimalist on-screen design.

4.25 A–B Netzspannung's Timeline

netzspannung.org/tools/knowledge-discovery

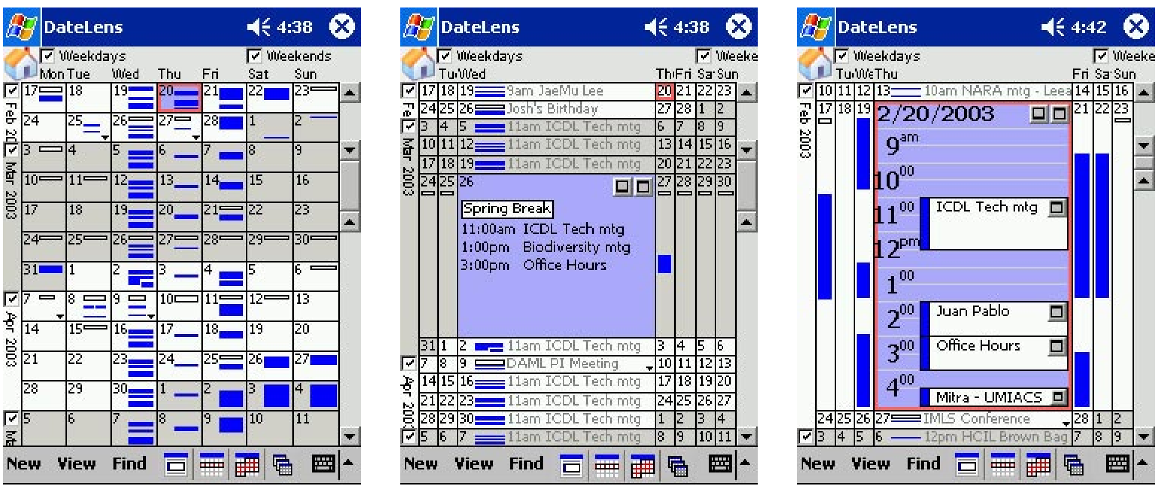
Netzspannung Timeline

Dynamic queries are useful for geographic GIS data, but also can be applied to visualizing temporally ordered information. Timelines are common in commercial film or animation softwares (Apple Final Cut Pro or Macromedia Flash, for example) and vary in structure based on required user tasks. This particular example, Netzspannung's interactive Timeline navigator (fig. 4.25), doesn't fit exactly the dynamic query

category but is a related example as the objects displayed can be altered in real-time by the user. Developed parallel to the Semantic Map (featured above), this is the second experimental interface to access the archive of projects from the Netzspannung MARS conference.

The design is composed of a time controller along the top and 7 horizontal sections below for different categories of documents. The time controller can be expanded or compressed by dragging the horizontal scale to reveal more or less years. In the time controller are blue squares representing archive objects, mapped in the sections below in the same relevant positions. A particular category can be clicked on to expand the height of the row and reveal thumbnail images for archive objects; all other rows have only text tags for each object.

The temporal scalability of this interface makes it a very useful visualization of objects along a timeline. As in previous examples of spatial distribution, the temporal distribution can be adjusted for an overview or zoomed in for detail. There are problems with the clarity of the object titles when the timeline is compressed, as the words and images overlap and become unreadable at a certain threshold. For clear navigation with readable project titles, the user must zoom in, and thus loses the overview of temporal distribution. This problem could be addressed with the implementation of a hyperbolic fish-eye visualization technique used by the *DateLens* (Bederson 2002), whereby a horizontal and vertical scaling is performed. The DateLens (fig. 4.26) looks similar to the hyperbolic tree (section 4.1.1), as the selected section of the timeline is expanded while the rest is compressed to the edges.



4.26 A-C DateLens interface for optimizing use of space on small screen displays such as PDA's.

image source: www.windsorinterfaces.com/datelens-screenshots.shtml

4.2.2 Chart

These visualizations, as with the examples in the previous section, illustrate contextual relationships among objects in digital archives. The section title *chart* refers to the geographic metaphor used by many of the examples, producing (2D or 3D) landscapes of the represented information space. These maps are interactive and usually allow a repositioning or zooming into the landscape to see more detail of a particular topic.

This section is divided into 3 categories: internet search engines, data landscapes, and virtual environments.

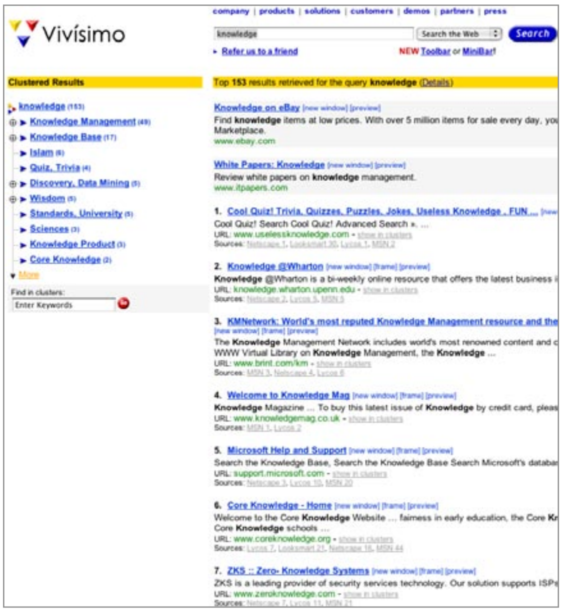
Internet search engines

In today's popular search engines, results are presented as a ranked list based on an algorithmic indexation of defined parameters, unique for each search engine (*searchenginewatch.com/webmasters/article.php/2167891*). Improvements on these search algorithms can be achieved by increasing the semantic indexation of the search results. Several examples are presented which present results with an ontologically classified structure.

Vivisimo

Vivisimo (*www.vivisimo.com*), fig. 4.27, is a company founded by Carnegie Mellon University researchers to market its data mining and text analysis software. Based on an algorithm which automatically clusters text documents into categories, the software has been applied to an internet

4.27 A–B Vivisimo search engine interface. On the left of each image are the expandable category listings.
www.vivisimo.com



search engine. The interface is text based and not mapped, but has been included in this report as an example of the benefits of semantic classification for information searching.

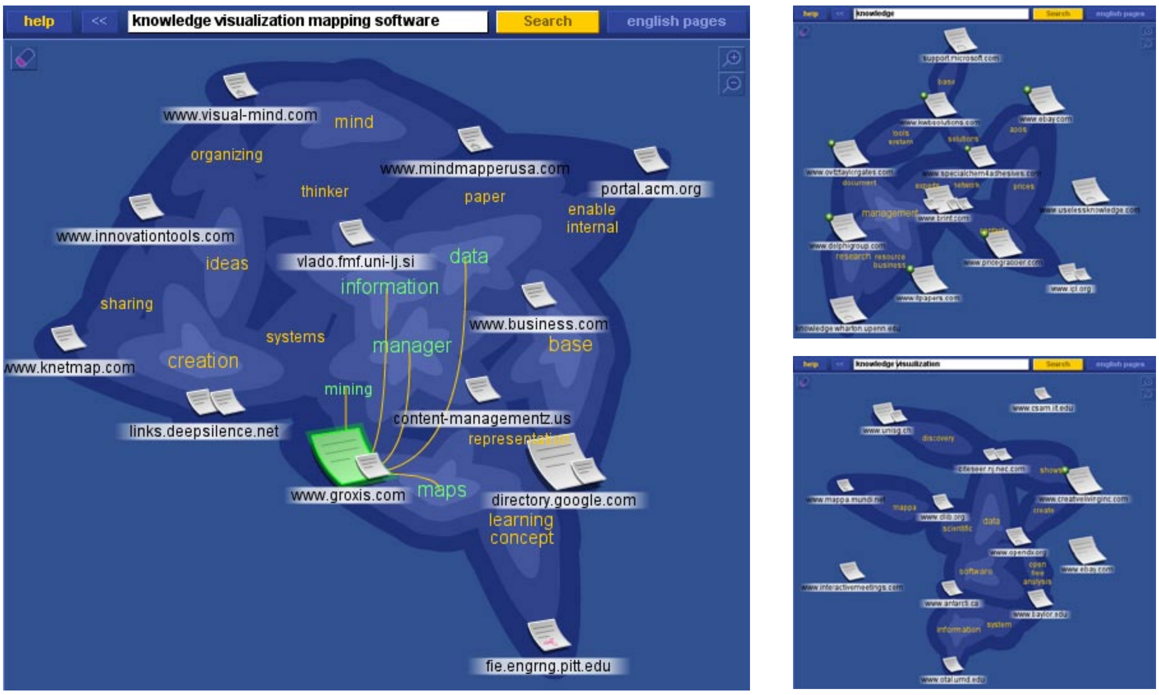
The interface contains a text field where one or more keywords can be entered. Users can filter the search to particular ranges of the internet, including specific news, information or commercial websites. The clustered results are presented as a text list along the left side of the web browser window. Each category can be further subdivided into sub-categories and browsed by clicking on cluster titles. Clicking on a category reveals a list of related pages in the centre of the browser.

Kartoo

Kartoo is a French company using a similar text analysis and clustering technology to Vivisimo. However, kartoo has developed an interactive cartographic visualization to the display of metasearch results. A very different internet search experience to browsing long Google lists, the kartoo map illustrates major semantic categories and uses an icon system to distinguish document formats and sizes (*www.kartoo.net/a/en/aide04.html*). A simple mouse click allows users to add search terms to their results and a rollover shows which key category names relate to a particular document. A new map is created for each additional keyword and the newly generated clusters are re-visualized together with the search results (fig. 4.28).

4.28 A-C Kartoo search engine showing maps for various searches. The left image shows the green highlight and connecting yellow lines that result from a roll-over.

www.kartoo.com



The interface, programmed in Macromedia Flash, is intuitive but a learning curve is required to decipher the iconography and options for interactivity. The document icons are large and as such only 10-15 result pages are shown for each search (compared with thousands of results with Google). An improvement to the interface could be made by reducing the icon sizes and implementing a pixel-cluster technique as with Krypthästhesie. This search interface is likely an indicator of the kind of visual searches that will be developed for the future semantic web.

Other websites featuring visual content searches include:

> *www.mapstan.com:* software download required before use
>
> *maps.map.net:* searches the *www.dmoz.org* open internet directory, using a map paradigm developed by *www.antarcti.ca*
>
> *www.webbrain.com:* a visual hypertext browser to the *www.dmoz.org* open internet directory
>
> *www.webmap.com:* an email to the company is required to access the TotalVIEW demo
>
> *www.miner3d.com:* browser plugin must be installed for visual internet search
>
> *www.plumbdesign.com/products/thinkmap:* website-based custom applications

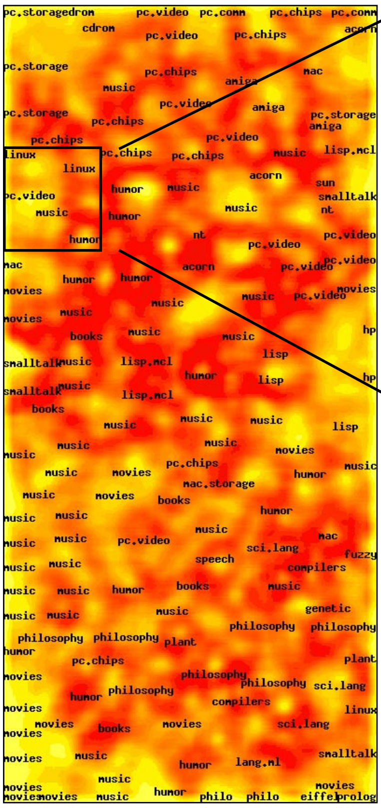
Data Landscapes

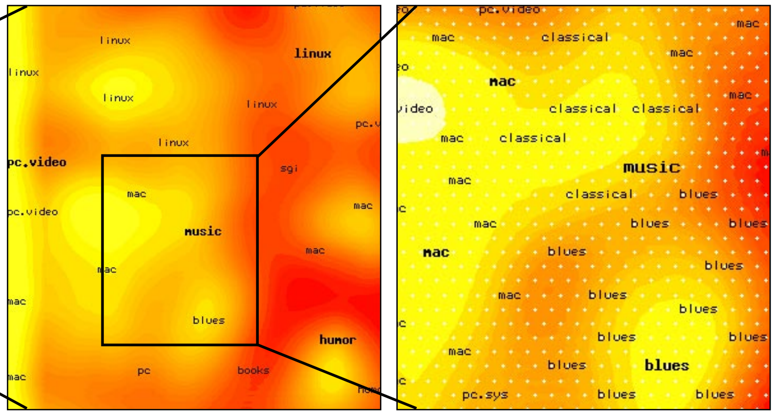
The Earth's topography reflects the diversity of mother nature and human culture; oceans, mountains, deserts, rivers and cities combine to form our planet's landscape. Centuries of cartographic experimentation have established a sophisticated science of abstracting the complexity of this physical space to graphic maps. Geographic maps and atlas images are ubiquitous and most people are exposed to these images in school, television or print media. The decoding and interpreting of cartographic maps is thus an ability already prevalent in mainstream culture. GIS (geographic information systems) softwares, such as Esri (*www.esri.com*), are specially designed to visualize data on geographic maps. The established range of graphic and technological techniques and the already map-literate mainstream public creates a perfect tool box for information visualization designers.

The space of information stored in digital archives is similar in vastness and complexity to natural topography. Many visualization experiments have taken advantage of cartographic techniques to produce readable information graphics. The analogy from physical landscape to data landscape is applied literally on contour terrain maps (*www.webmap.com*) and in others provides a metaphor as a point of departure. This section features a couple of these examples.

WebSOM

The Kohonen "self-organizing map" (SOM) algorithm was developed in Finland to organize large (millions of documents) archives based on textual similarities. The system draws from theories of "*self-organization, associative memories, neural networks, and pattern recognition*" (Woolman 2002, 45). The algorithm produces 2D maps based on a grid where related documents appear close together.





These example images (fig. 4.29) are screenshots from the online demo, a visualization of over a million documents from 80 Usenet groups. Usenet discussion topics are labelled and colour-coded based on the density of documents from a particular topic. The map can be zoomed into twice by clicking, after which white dots appear which represent particular discussion threads. Clicking on a white dot opens a text window containing links to discussion messages. In some sections of this map the logic of the semantic clustering is not apparent as unrelated themes appear beside one another (i.e. "music" is surrounded by "linux").

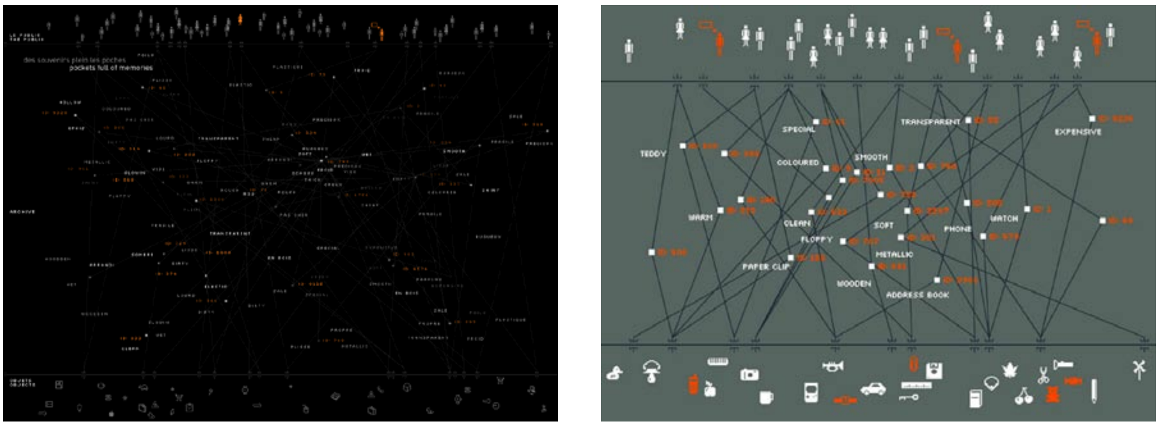
4.29 A–C **WebSOM self-organizing map. Three levels of zoom are shown, increasing from left to right. The black squares indicate the section that has been zoomed into.**

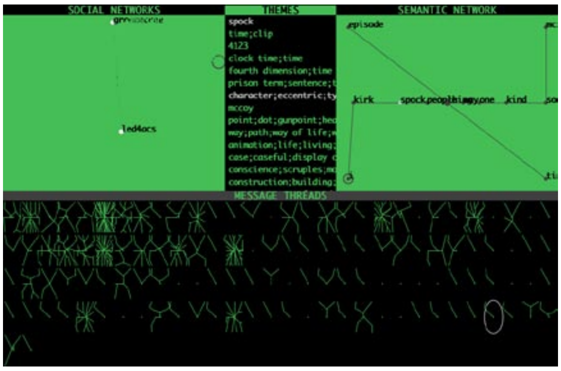
websom.hut.fi

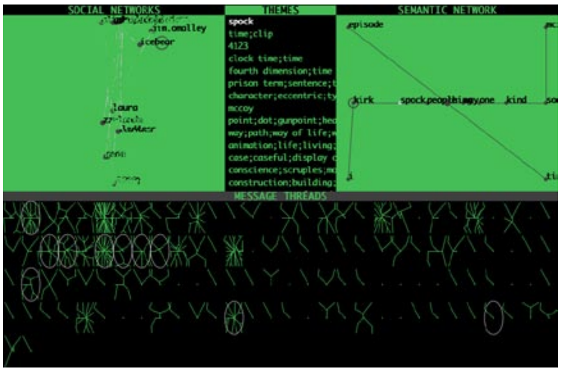
In a different application of the Kohonen algorithm, it was used by digital artist George Legrady (fig. 4.30) to develop the visualization for the *Pockets Full of Memories* project exhibited at Ars Electronica (*www.aec.at*) in 2003.

4.30 A–B **George Legrady**
www.georgelegrady.com

Pockets Full of Memories
www.pocketsfullofmemories.com

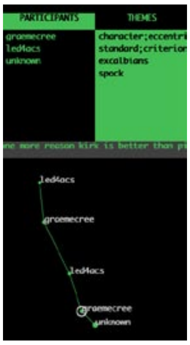






Conversation Map

This project, as with the WebSOM example, is a visual browser for Usenet discussions. It is included in this section of this report as a comparative example of a different approach to visualize similar content (while it does *chart* Usenet discussions by visualizing their dynamics, it does not use a geographic landscape metaphor). The Java web-based interface was developed by Warren Sack as part of his doctoral research in the analysis of "Very Large-Scale Discussions" (VLSDs). Incorporating text analysis procedures from computational linguistics and quantitative sociology (*www.sims.berkeley.edu/~sack/cm/how.html*), archives of usenet discussions are quantitatively assessed for social and semantic characteristics.



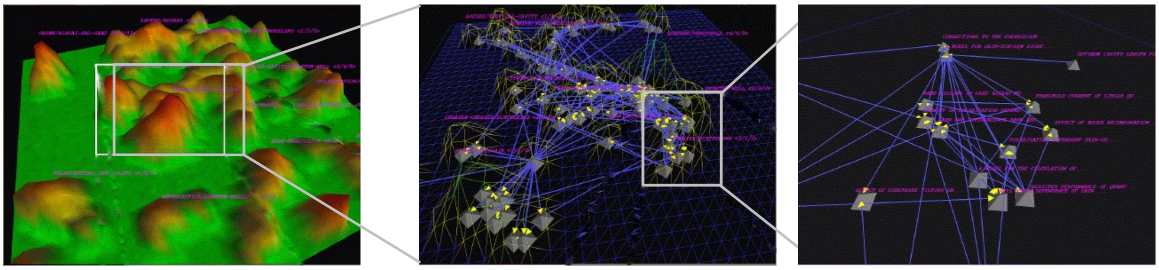
4.31 A-C Conversation map screenshots.

www.sims.berkeley.edu/~sack/cm

As pictured in these screenshots (fig. 4.31) of a visualization of Star Trek usenet discussions, the interface is divided into 4 parallel views of the same usenet group: "social networks", "themes", "semantic network", and "message threads". Each panel is interactive and linked to the other panels; the visuals change when a certain user choice is made by clicking on an item. While the graphic quality of this project is questionable (the interface is cryptic, the visual elements jumpy and the typography not very readable), this system could be a powerful resource for researchers assessing the dynamics of on-line discussion.

VxInsight

The VxInsight (fig. 4.32) knowledge management tool was developed by Sandia National Laboratories, a US government lab occupied largely with military research. The software visualizes data from large databases, illustrating search results as a 3D mountain range landscape. Each mountain represents a cluster of documents from a particular area and the height represents the number of documents in the cluster. A panel of



4.32 A–C **Vxinsight screenshots. The three levels of zoom increase from left to right. The grey lines indicate the zoomed sections. The image on the right allows "details-on-demand"; further information about objects when clicked. Information about this and other projects are available at :**

www.pnl.gov/InfoViz/ technologies.html

controls allows the user to highlight documents (shown as coloured dots) based on certain parameters. A zoom function enables a mountain to be zoomed into to show further detail, such as hypertext or citation references between individual documents. An interesting feature is the time parameter definition bar which enables the landscape to be set and scanned through specific time periods, allowing temporal trends to be discovered.

The Pacific Northwest National Laboratory, a US military research lab, has developed a package of visualization tools called SPIRE (Spatial Paradigm for Information Retrieval and Exploration). The lab's website (*www.pnl.gov/InfoViz/technologies.html*) contains images and descriptions of several of these programs. Many use interesting visual and interaction paradigms, and to give an idea of metaphors employed, some names of these tools are *Galaxies*, *Starlight*, *Rainbows*, and *Cosmic Tumbleweed*.

Virtual Environments

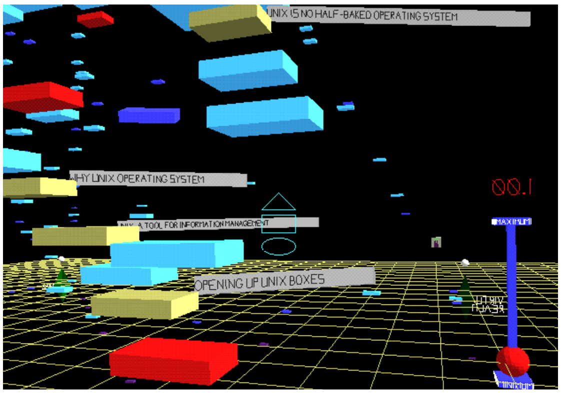
A promising research area is the integration of data visualization into navigable 3D virtual worlds. The extension of information maps from flat 2D planes into the third dimension adds a different range of interactivity and complexity. As *Web3D* (Web3D Consortium, *www.web3d.org*) technologies evolve from VRML to X3D (Chen 2003b, 92) and integrate XML for the semantic web, there is developing a standard platform for web-based virtual environments. These worlds, as with many of today's computer games, can be set up as collaborative workspaces as they can be explored by one or more users simultaneously. Chaomei Chen's book *Information Visualization and Virtual Environments* (1999) discusses some of the salient issues in integrating virtual reality with information and presents some key applications. Two research projects are described to illustrate the potential of this area.

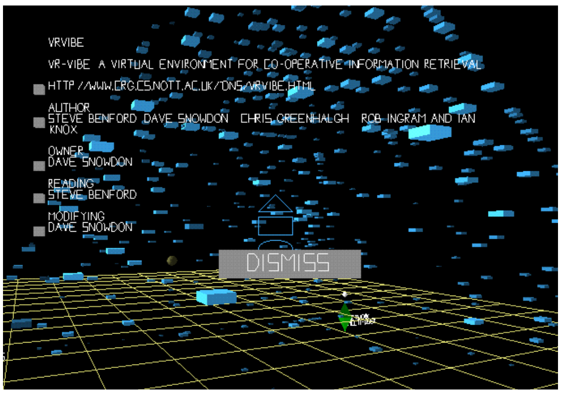
Populated Information Terrains (VR-VIBE)

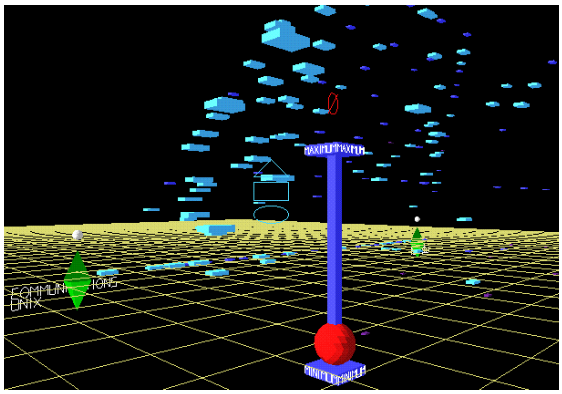
The Communications Research Group at the University of Nottingham has developed a set of visualization techniques called Populated Information Terrains, or PITS (*www.crg.cs.nott.ac.uk/research/applications/pits*). PITS are multi-user virtual reality applications in which users are embodied in the environment and visible to each other. One of these projects, called VR-VIBE (fig. 4.33), visualizes a bibliographic archive by representing documents as 3D shapes. Users can input keywords directly into the 3D space, whereupon the document objects are rearranged and coloured based on statistical semantic relevance. Documents can be flagged for future reference, and when clicked on a summary of bibliographic details is shown in the foreground. Other users are illustrated as simple shapes, and all users can dynamically and collaboratively respatialize the objects by moving the keywords.

4.33 A-C VR-VIBE screenshots

image source: www.crg.cs.nott.ac.uk/research/technologies/visualisation/vrvibe



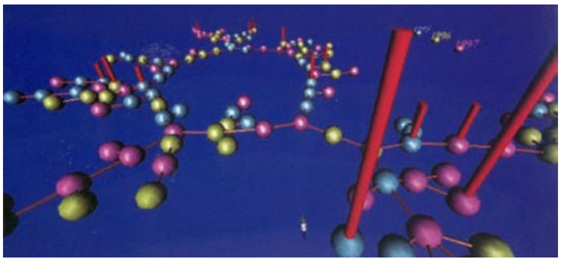


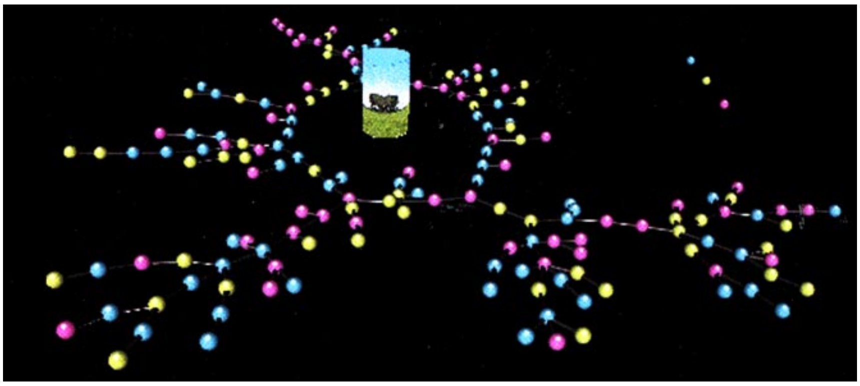


Starwalker semantic constellations

The Starwalker (fig. 4.34) is multi-user VR environment which arranges document objects in 3D space based on semantic relevance. The design rationale behind this project is to study social aspects of collaborative research, or as stated by the designer, "*(if the) virtual environment can reflect the underlying semantic structure of an abstract information space, then users may develop more engaging social interactions*" (Chen 1999, 189). The system encourages scholarly exchange by researchers who can discuss in a chat window and achieve a sort of "collaborative sense-making" (Chen 1999, 190). This experiment attempts to integrate semantic, spatial, and social structures to create a contextually coherent place out of an abstract information space (Chen 1999, 190). Extensive research has been documented on the dynamics of social interaction within the Starwalker world (Chen 1999, 199).

As with VR-VIBE, documents (a collection of conference papers) are represented in VRML by 3D objects which are proximally arranged based on a semantic indexation. These spheres are arranged into a "PathFinder" network of links and hierarchical classifications, and colour-coded by publication year. A roll-over onto a document sphere shows the title and a click shows the abstract in a linked browser window (Dodge 2001b, 143). Vertical bars are connected to the spheres to illustrate the volume of citations to the particular paper.





4.34 A-B Starwalker Semantic Constellations screenshots.

Chaomei Chan homepage:
www.pages.drexel.edu/~cc345

image source:
Woolman 2002, 110-111

4.3 Visualizing Dynamics

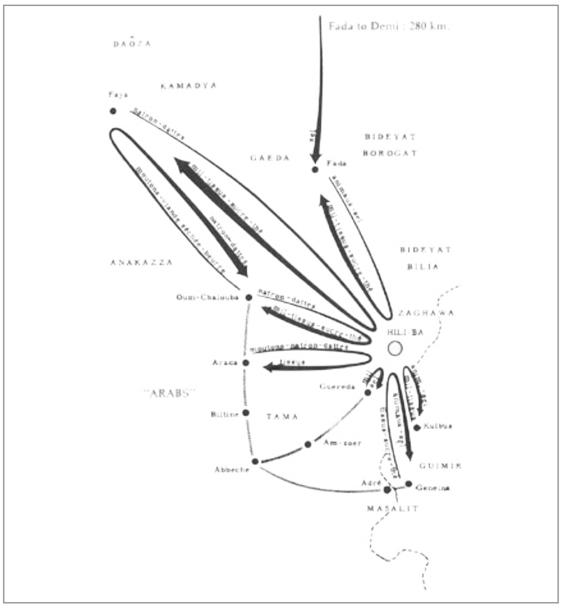
In our contemporary society of ubiquitous networked real-time communication, the dynamics of cultural architectures are in shift. Analysts such as Manuel Castells, Zygmunt Bauman, and Arjun Appadurai have commented on the increasing "flow" or "liquidity" of modern cultural structures in spheres of technology, politics, economy, media, ideology, and nationality. Strategies to visualize these phenomena will aid in research and analysis. A recent Doors of Perception design conference was entitled *Flow* (*flow.doorsofperception.com*), and featured a collection of speakers discussing various aspects of this phenomenon. Much of the discussion revolved around techniques to interpret and visualize flow dynamics.

Following are descriptions of projects which utilize various approaches to represent fluxes, flows, and evolutions through space and time. The examples are organized into two categories:

> *Flow* - illustrating the path or quality of a continuous motion. The sub-sections are *space*, *communication*, *sequence and language*, and *process*.
>
> *Evolve* - revealing a trail of influence or changes in a system over time. The sub-sections are *hand-graphics* and *computer-graphics*.

4.3.1 Flow

Space



4.35 A–B Visualizing direction and magnitude of flow in a vector field.

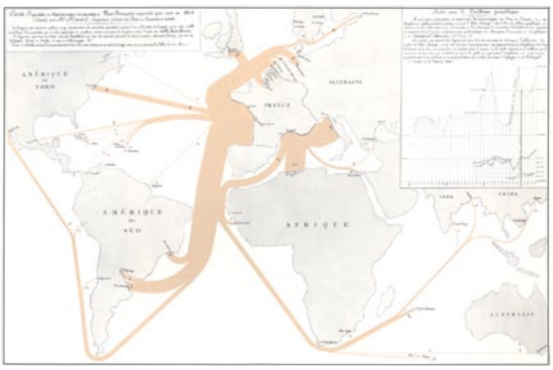
image source:
Bertin 1974, 356-358

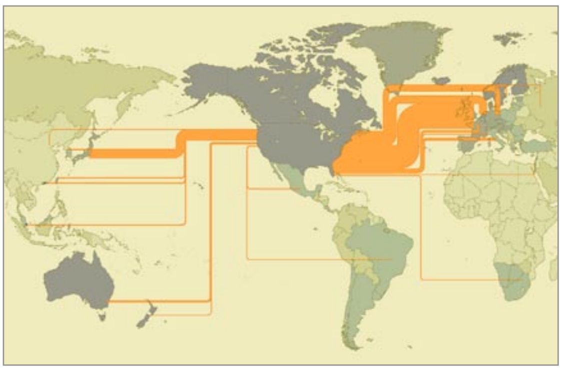
An extensive study into the use of graphical elements for to visualize various aspects of information was published by Jacques Bertin in the classic text *Semiology of Graphics* (1974). These images (fig. 4.35) from Bertin's book illustrate the use of arrows of varying paths and thicknesses to show movement within a vector field on a geographic map.

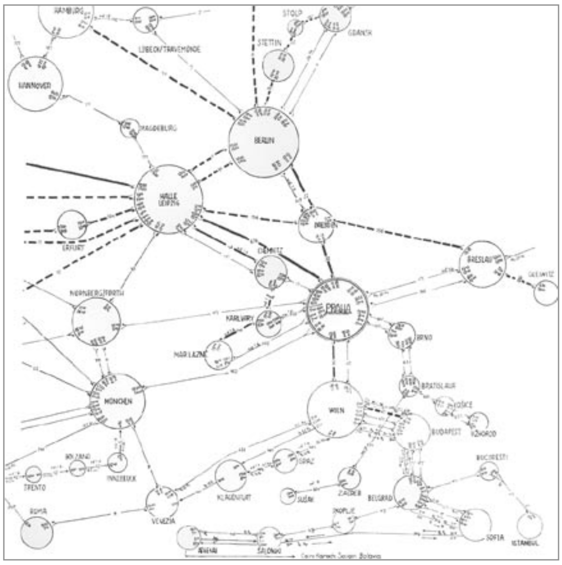
These two maps below (fig. 4.36) show a technique used to illustrate a quantified movement through geographic space. The image on the left is from Charles Joseph Minard, a legendary innovator of data graphics active in France in the mid 19th century. Minard's graphic illustrates the exports of French wine in 1864. The image on the right shows intercontinental internet bandwidth as of mid-2000. The same graphic strategy applies to the movement of wine as to the flow capacity of digital data; flow magnitude map to line width and geographic paths to line location.
Another example of a modern adaptation of a classic technique is given

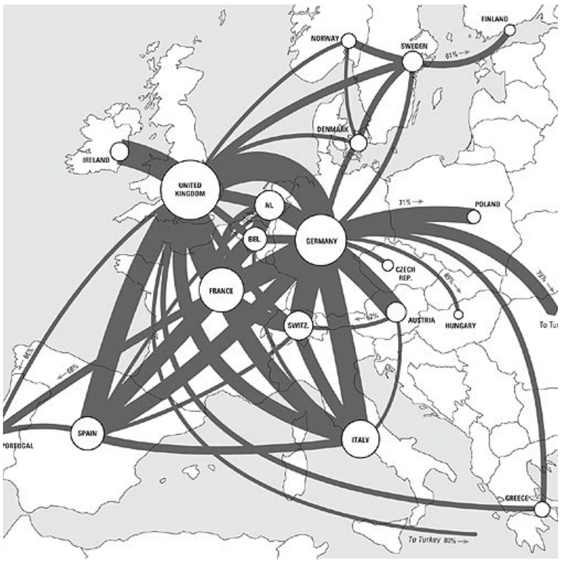
4.36 A–B Quantified flow along geographic paths.

image source:
***left:* Tufte 1983, 25**
***right:* PriMetrica Inc.© 2004**
www.telegeography.com









4.37 A–B **Quantified flow within a network of geographic locations.**

image source:

left: **Tufte 1990, 102**

right: **PriMetrica Inc.© 2004**
www.telegeography.com

by the above maps (fig. 4.37). On the left is a graphic schedule from the Czechoslovakia Air Transport Company in 1933. The circles locate cities and are sized proportionally to the flight traffic through the city. An outstanding aspect of this map is that the times of flight departure and arrival and the flight numbers are integrated into the geographic topography. On the right is a map, also by Telegeography, which illustrates European usage of telecommunications networks in 1999. Country circles are sized proportionally to the total outgoing traffic, and the thickness of the lines is proportional to the traffic between two particular destinations.

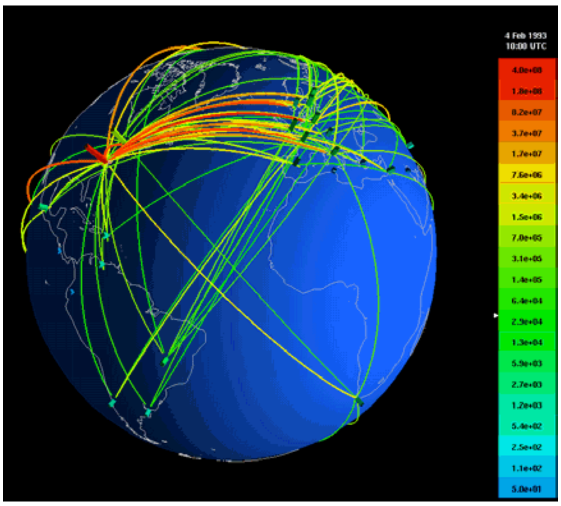
4.38 A–B **SeeNet3D software for quantified network flow. Colour represents magnitude as illustrated by the scale on the far right.**

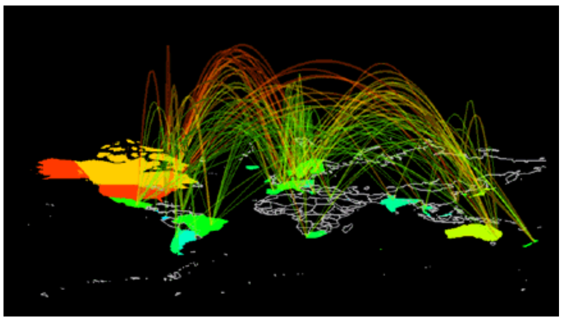
www.bell-labs.com

image source:
www.cybergeography.com

SeeNet3D

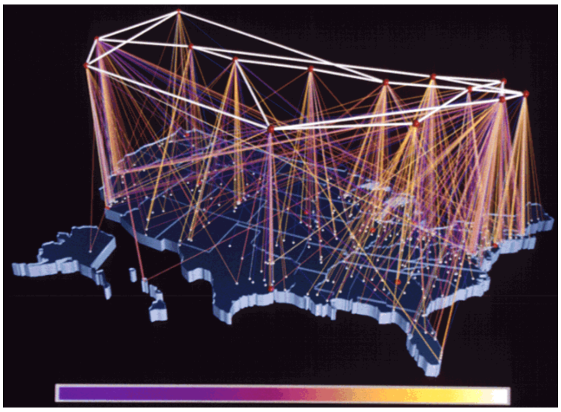
Stephen Eick and fellow researchers at Bell Labs in the late 1990's developed techniques to visualize geographic network flows (fig. 4.38) (Eick 1996). They designed the "SeeNet3D" software to produce images in 3D using colour of lines (not thickness) to represent flow quantity. Presented here are 2 images from that research; notice the use of partially translucent arc lines in the map on the right, which reduces visual clutter.





NSFNET network analysis

At the NCSA (National Centre for Supercomputer Applications, *www.ncsa.uiuc.edu*) in the early 1990's, Donna Cox and Robert Patterson developed animated visualizations to show the exponential growth of internet data flow. This image (fig. 4.39), from 1991, illustrates the volume of inbound traffic on the NSFNET internet network to various locations in the USA. Lines are colour coded to data flow magnitude on a scale of 0 bytes (purple) to 100 billion bytes (white).



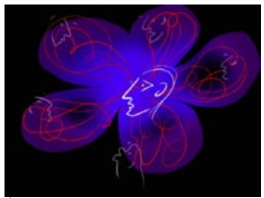
4.39 NSFNet network analysis

image source: archive.ncsa.uiuc.edu/SCMS/DigLib/text/technology/Visualization-Study-NSFNET-Cox.html

Communication

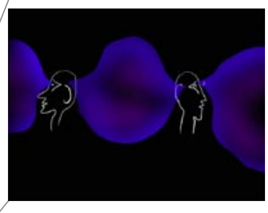
Dynamics of social interaction

Marco Susani and his research group at the Advanced Concepts Design Group of Motorola are interested in analyzing the dynamics of social exchange by various media in order to improve system design. These images (fig. 4.40) are illustrations of different social spaces and situations enabled by communications media and related to the personalities of people.



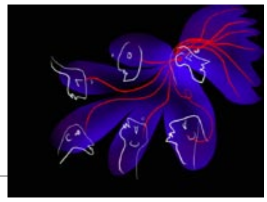
intimate daisy

a person with a group of close friends



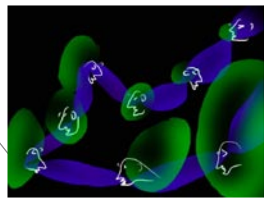
butterfly

two people exchanging information and passing it on to others



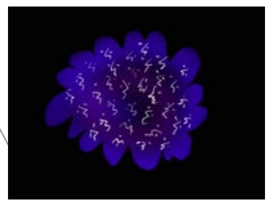
crest

a group leader gathers information and distributes it



pearl

a message is passed on from person to person, mutating along the way



sunflower

a large social gathering full of discussion

4.40 A-E *image source:* flow.doorsofperception.com/content/susani_trans.html

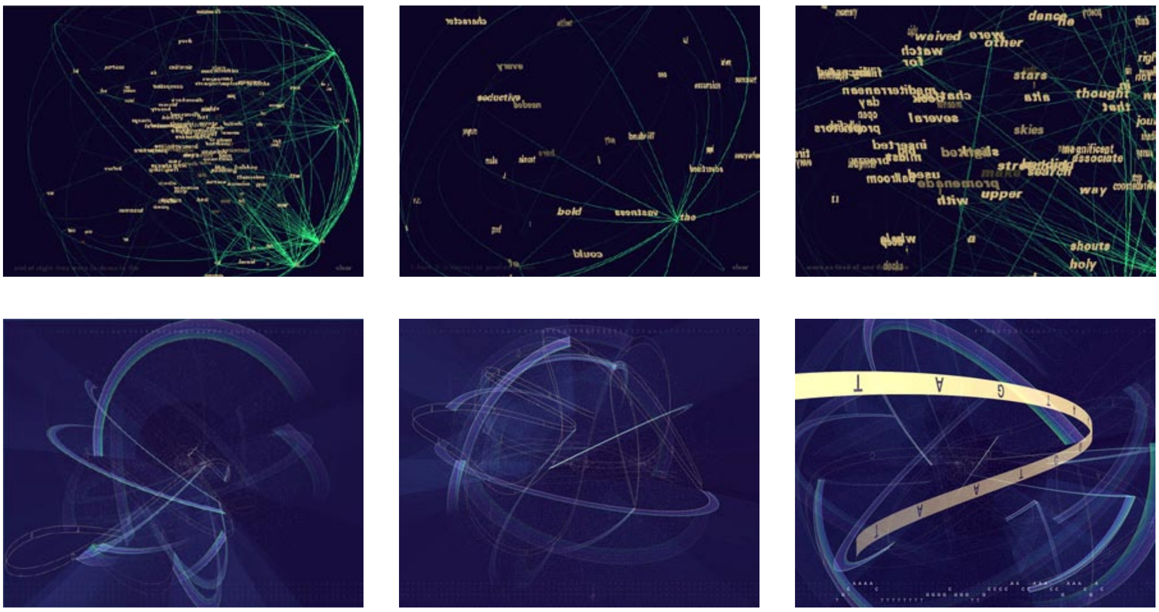
The study of social networks is a growing area of research. As with internet topology maps which aid in network analysis, social network visualizations can help in understanding the dynamics of social groups. Internet sites (*www.friendster.com, www.linkedin.com, www.tribe.net*) have sprouted in recent years which allow users to connect with each other by constructing and mapping social networks. Interesting scientific research is being performed by organizations such as the FAS (*www.fas.at*) in Austria, who are using visualization to analyze social groups. A unique approach was taken by artist Mark Lombardi who charted celebrity social networks to expose scandalous associations among political and financial figures. Lombardi developed a refined graphic syntax to produce elaborate hand-drawn diagrams.

Sequence and Language

The next few examples deal with language (or symbolically encoded information) and the dynamics of its composition.

Valence

These images (fig. 4.41) are by Ben Fry of the MIT media lab, whose Valence software visualizes long sequences. Mr. Fry has a rare combination of superb programming skills and an excellent aesthetic eye, and has developed some of the more elegant information visualizations in recent years. His graphic style is often a refreshing change from the rigid designs of some programmers. His interactive visualizations of large and dynamic data sets seem to follow Edward Tufte's principles for designing information graphics (Tufte 1983). The top three images are captured from the online Java applet of Valence reading text from Mark Twain's book *The Innocents Abroad*. The bottom three images are from a later version



4.41 A-F Ben Fry's Valence (top) and GenomeValence (botttom).

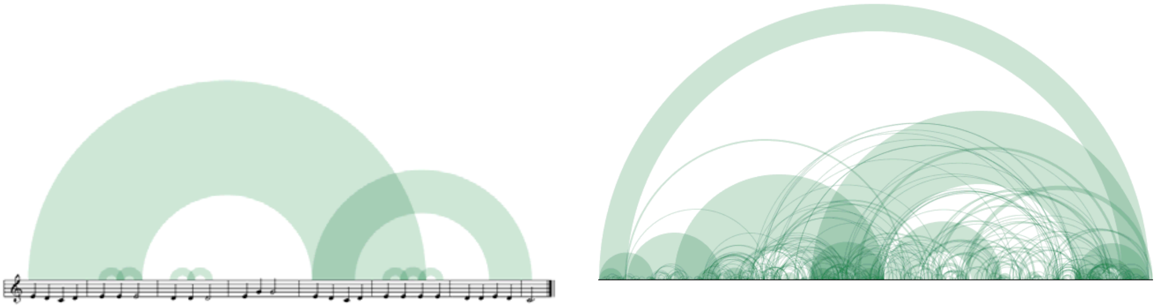
acg.media.mit.edu/people/fry/valence

acg.media.mit.edu/people/fry genomevalence

of Valence called GenomeValence, a visualization of a sequence of DNA genetic code. A related approach to software text visualization, called Textarc (*www.textarc.org*), was done by media designer W. Bradford Paley.

Arc Diagrams

Developed by data visualization innovator and IBM researcher Martin Wattenberg, these images visualize the contents of long sequences. Encoded information, such as language, music, or DNA, contain long sequences of characters, often with repeating sections within. These images, called Arc Diagrams (fig. 4.42), are visualizations of musical compositions in which repeating sections are linked by looping curves. The left diagram shows the simplicity of *Mary had a little Lamb* and on the right the complexity of Beethoven's *Für Elise*.



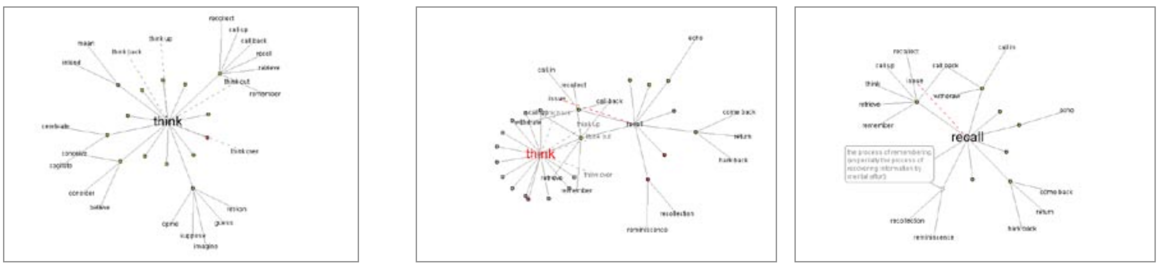
4.42 Martin Wattenberg's Arc Diagrams.

www.turbulence.org/Works/song

***www.mw2mw.com* (other projects)**

Visual Thesaurus

Visual Thesaurus (fig. 4.43), a Java applet created by Plumb Design, is an online animated interactive thesaurus that visualizes the connections between semantically related words. A word can be searched for and is subsequently shown with related words connected by lines which branch off from the centre. A roll-over shows the definition of the word and a click initiates an animation into a new tree of the word clicked on. The interface is customizable and a drop down menu gives the user control over various parameters including colour contrast, line length, and font size. The trees can be viewed in 2D (as shown in the screenshots) or quasi-3D in which the word tree can be rotated around the central node in spherical coordinates. The interface and typography are cleanly designed and the interface is intuitive. Some improvements could be made to the algorithm that sets the positioning of the words as their jerky movements reduce readability.

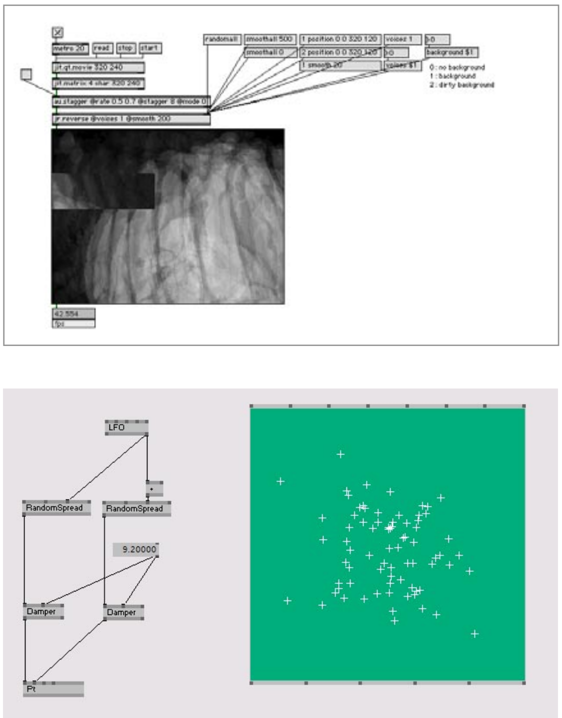


4.43 Visual thesaurus screenshots. The image on the left shows the semantic tree for the word "think" and the image on the right shows for the word "recall". In the centre is a capture of the transitional animation from the one word to the next.

www.visualthesaurus.com/online

Plumb Design: *www.plumbdesign.com*

Process



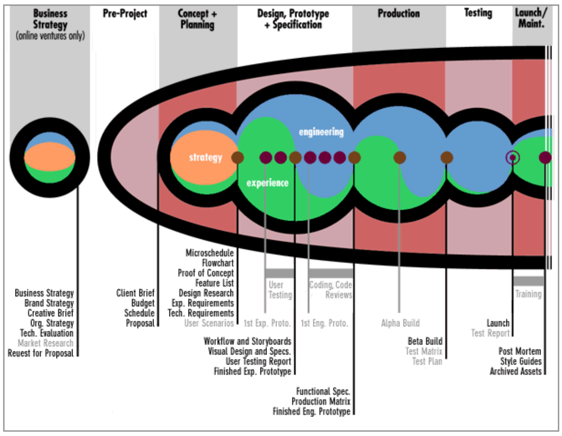
4.44 Jitter (top):
www.cycling74.com/products/maxmsp.html
image courtesy of Jeremy Rotsztain

vvvv (bottom):
vvvv.meso.net

Graphical programming

As the Visual Thesaurus creates a linguistic chain by connecting words, graphical programming languages allow users to manipulate a data flow chain by connecting program objects. Contrary to text programming, graphical programming is contained within a visual GUI (graphic user interface) environment in which programs are composed and tweaked with graphic objects. This allows programmers to visually track and manipulate the data path.

Presented here are screenshots (fig. 4.44) from 2 different graphical programming environments: Max/MSP Jitter (top) and vvvv (bottom). The grey boxes are the functions and operations ("nodes") and when linked form the program ("patch"). Individual node parameters can be adjusted by dragging on the tiny dark boxes on the node corner, and the results can be viewed in real-time in the output window.



4.45 Nathan Shedroff's product development process diagram.

www.nathan.com/thoughts/process/index.html

Process diagram

American experience-designer Nathan Shedroff has written extensively on the design process. This diagram (fig. 4.45) is a graphic summary of the stages in designing an interactive product. With clever use of text, colour, and curves, the various procedural stages are effectively visualized in terms of task requirements and sequential order. The image requires verbal explanation for a complete explanation of the concepts, but it succeeds in succinctly expressing the essential ideas.

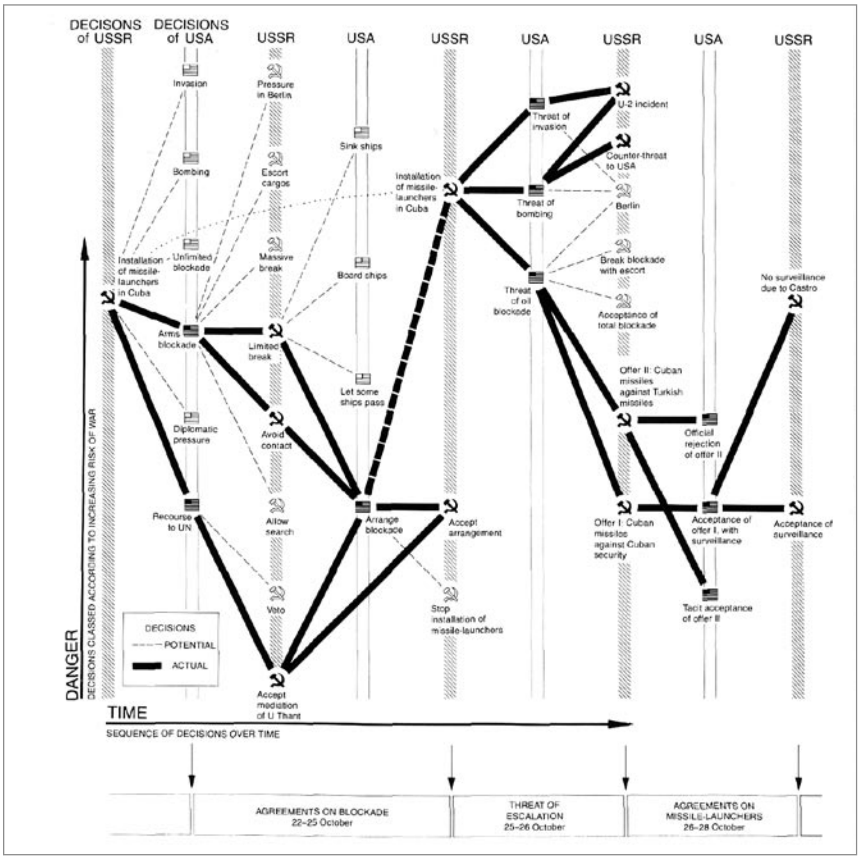
4.3.2 Evolve

The examples in this section illustrate the key events or changes that occur in a system over time. For the sake of organization, the selections have been divided into 2 sections: *hand graphics* (less complex data, no computer used for image production) and *computer graphics* (complex data, computer aided data analysis and image production).

Hand Graphics

This small section features selections from the books of information graphic design gurus Jacques Bertin and Edward Tufte. These images were produced without computer assistance for data analysis or image production. The examples demonstrate the power of good design by showing the density of information that can be expressed in static images. These images are scanned and reduced in size and may not be of perfectly readable quality, but the ideas should be evident.

Historical events: the Cuban missile crisis

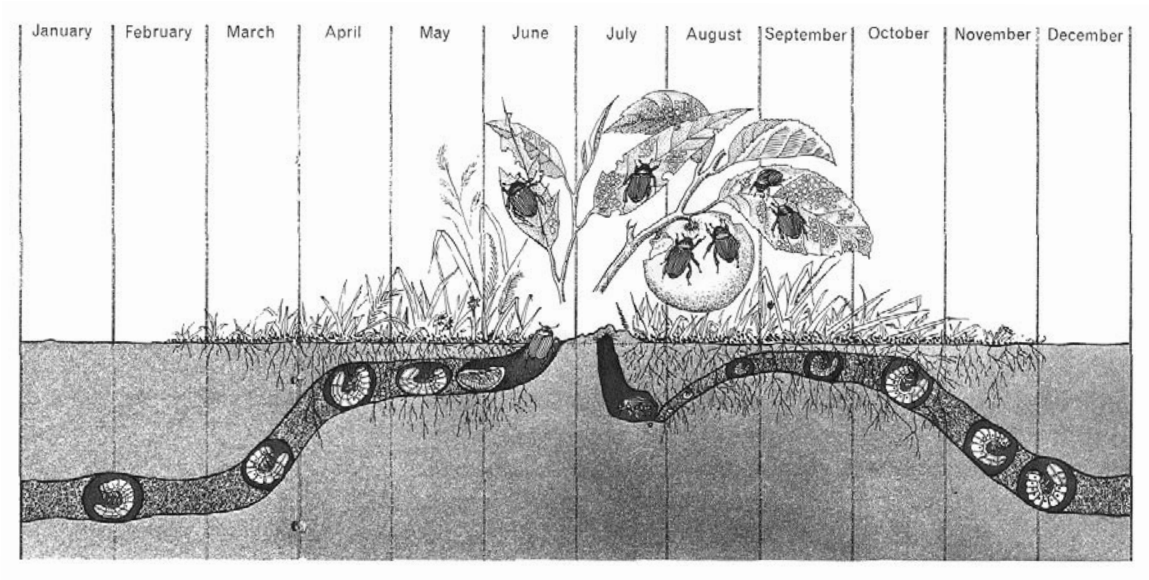


4.46 Cuban missile crisis historical diagram. It tells a detailed historical story, mapping every decision (both actual and potential) faced by US and Russian governments over time (horizontal axis) and rated on a danger scale (vertical axis).

image source:
Bertin 1974, 272

The diagram (fig. 4.46) on the previous page recounts the sequence events of the Cuban missile crisis between the USA and Soviet Union from Oct. 22-28, 1962. The graph contains much information and, while it does not allow an immediate interpretation, with a prolonged reading it facilitates an extensive analysis on the historical situation. An elegant example of mapping applied as an abstraction of a real event (as geographic maps are abstractions of a real space), the same story would take pages of written text to tell by linguistic means.

Beetle life cycle



4.47 Beetle life cycle diagram
image source:
Tufte 1983, 43

This illustration (fig. 4.47) shows the annual life cycle of a beetle. The image is divided into twelve vertical panels, one for each month of the year. Each panel shows the position, size and activity of the beetle during that month; from metamorphosis in early June to feeding on leaves in mid summer to winter months as an underground larvae. The image shows the progression of time along the horizontal axis and is effective in its blending of the twelve panels into one coherent image.

It is interesting to note a cultural bias in this image as with many time-based examples: time proceeds from left to right as with latin text or numbers. The image might be more difficult to decode for an individual used to reading right-to-left or top-to-bottom.

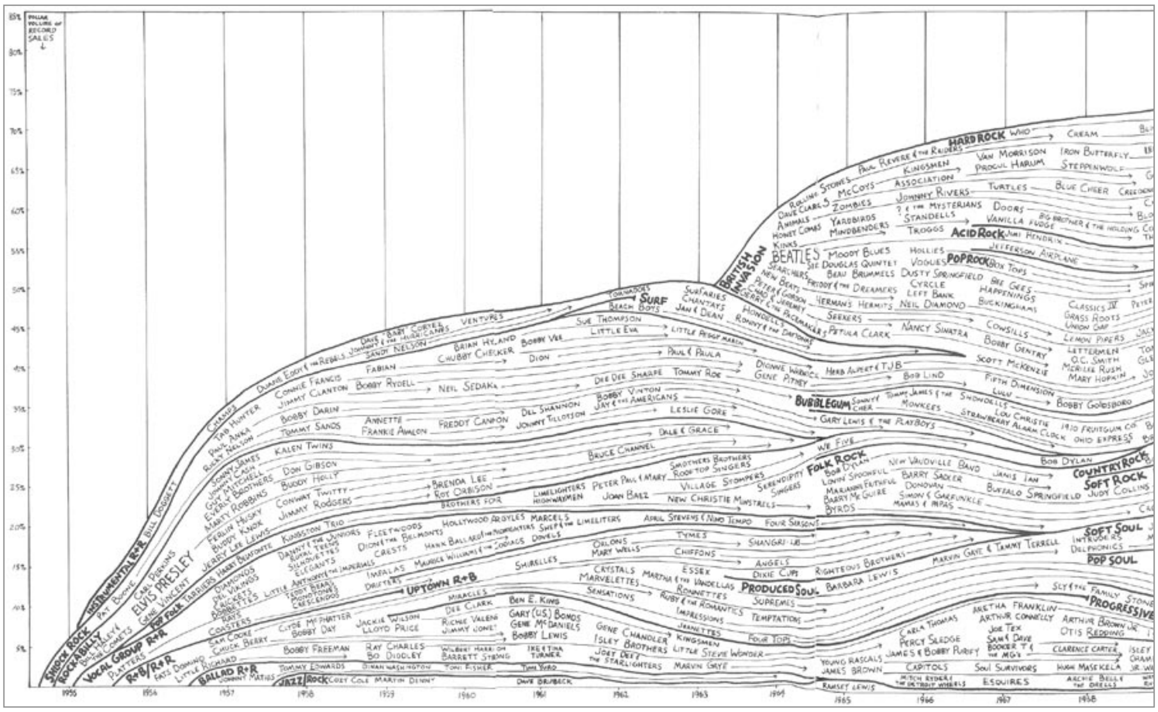
Music evolution

This map (fig. 4.48) tells the story of the evolution of rock 'n roll music from the mid-1950's to the mid-1970's. Time advances to the right along the horizontal axis and the volume of record sales increases up the vertical axis. Arrows and curved lines delineate the trail of influence over time, showing which musicians played which genres of music and for how long. Musical genres are indicated in bold lettering, and thin vertical lines measure each year. The map can be read horizontally for an overview of the evolution of the music, and it can be read vertically to get a snapshot of the star performers at a given point in time. The aesthetic of the drawing are appropriate to the content; all drawing is by hand, giving it a retro feeling that harks back to those golden years of rock 'n roll. This image is exemplary of good design in the density of information expressed with an optimal use of ink.

4.48 Beetle life cycle diagram

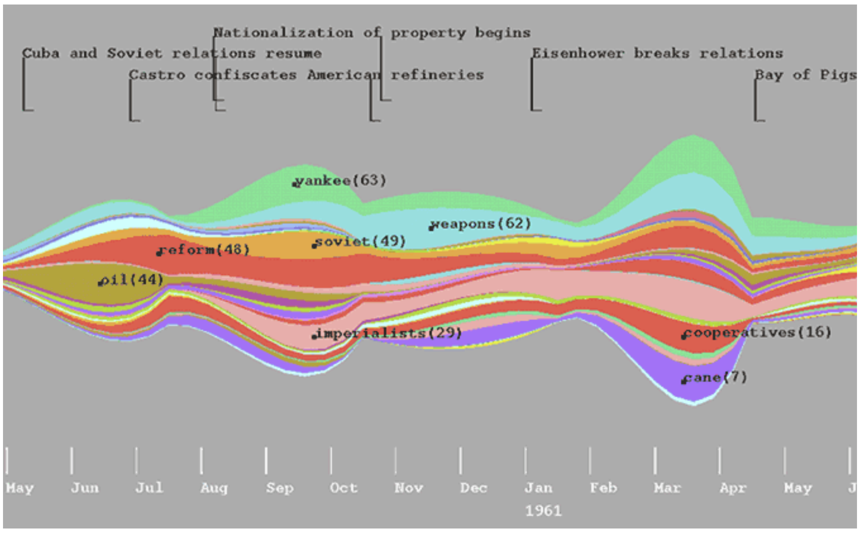
image source:

Tufte 1997, 90



Theme River

ThemeRiver (fig. 4.49) is an application from the aforementioned visualization research group of the Pacific Northwest National Laboratory. It is designed to help recognize trends in document collections over periods of time. At a given point in time, the major themes (in an archive of news articles, for example) are represented by coloured bars ("currents") which have a thickness proportional to the statistical strength of the theme. These currents are drawn together (to form a "river") from left-to-right and change in thickness as the relevance of the themes change over time. The image pictured here show the relevance of themes in news reports leading to the Bay of Pigs US invasion to Cuba in April, 1961. The bulge on the right side of the image shows the increasing significance of themes relating to the crisis at that time.



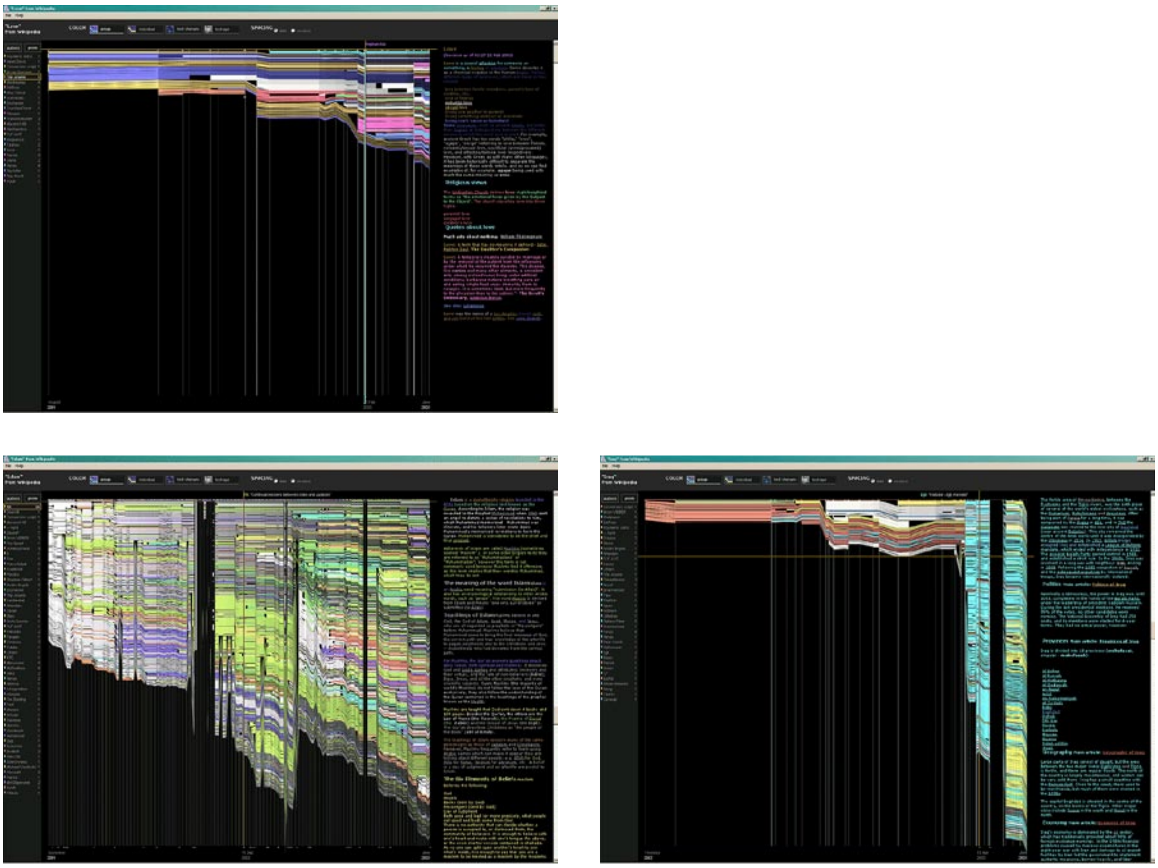
4.49 ThemeRiver screenshot.
www.pnl.gov/InfoViz/technologies.html#themeriver

History Flow

Another project by Martin Wattenberg at IBM's Collaborative User Experience Research Group is History Flow (fig. 4.50). These images, using a similar technique as ThemeRiver, visualize the evolution of dynamic documents produced collaboratively by multiple authors. Each author is colour coded, and a version of the article is represented by a line of vertical coloured sections for each author. The lines are distributed on the horizontal time axis and similar colours are connected by coloured bars to create bands of colour. A more detailed explanation is available on the project website.

The maps answers questions about the changes in a collaborative document over time such as:

> *Is there one or more authors?*
>
> *Who has contributed most to content production of a particular version?*
>
> *Has the production occurs in spurts and starts or in with more regular burst of activity?*



4.50 IBM's History Flow screenshots. These images are generated from analysis of documents from *www.wikipedia.org*, a free online encyclopedia open for the public to edit article contents. Pictured, from top-left through to bottom-right, are graphs from the articles "Love", "Islam" and "Iraq". It is interesting to see the rapid increase in content in the Iraq article (bottom-right) in April, 2003 at the time of the US invasion .

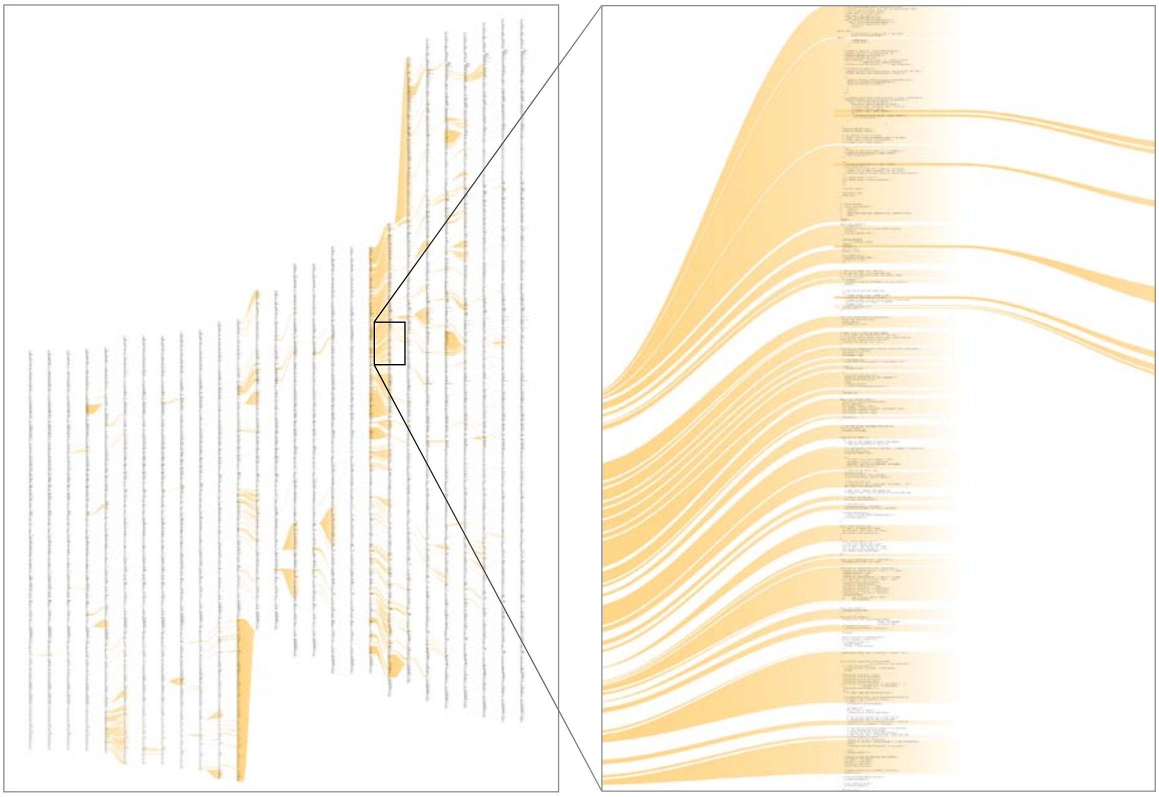
researchweb.watson.ibm.com/history

Revisionist

Another Ben Fry project, called Revisionist (fig. 4.51), visualizes the evolution of software code. The images, originally printed on large panels, show the changes in lines or sections of code over time. Each version of the project code is listed in a column, and the columns are connected by coloured curves where ever there has been a change. Large spurts of activity (before a public version release, for example) can be spotted by dense coloured areas. These images visualize the development of the Processing (*www.processing.org*) project over time.

4.51 On the left, a panel from the Revisionist project, originally printed in large format to show all changes at once. On the right, a detail zoom into a small section.

acg.media.mit.edu/people/fry revisionist



This is the final example in the survey of the state-of-the-art in information visualization. The examples, category system, and discussion presented above have given an overview of a broad range of application-specific visual and interactive techniques. The next chapter, having synthesized the survey examples along with the theory from previous chapters, will describe a platform for the development of a visualization design theory.

5 Designing Knowledge Visualization

This section introduces a basis for approaching knowledge visualization design. The discussion that follows is composed of three main sections: a exploration of sources of inspiration for visualization design, a summary of visualization techniques, and a presentation of guiding design principles. The idea behind combining these sections together is to provide a general basis for the creation of specific visualization applications and a foundation from which a more encompassing visualization design theory can be extended.

5.1 Aesthetics and Inspiration for Visualization Design

Before getting into a brief analysis of the survey examples and the elaboration of general design principles, this section contains a exploration of potential sources of aesthetic and conceptual inspiration for visualization design. Examples of visualization applications are presented which are not necessarily knowledge maps, but which explore in some way the aesthetics, representation, or spatialization of complexity.

The survey (section 4) was composed of examples mostly from with the research domain of information visualization. This is an emerging scientific field, with journals, textbooks, websites and conferences being initiated within the last few years. The discourse within the research community is mostly centred on work from technically-oriented computer science and engineering labs (see books such as Card 1999; Chen 2003a; Spence 2001; Ware 2000; also of note are accepted papers at information visualization conferences, such as IV'2004 in London). Within the digital arts community, on the other hand, is a parallel discourse regarding visualization aesthetics and interaction design experimentation (see the Ars Electronica festival proceedings, *www.aec.at*). This artistic community consists largely of individuals with a background in graphic design, typography, architecture, interaction design, and visual or media art. Unfortunately, there has been limited exchange and collaboration between information visualization scientists and designers or artists. Both scientific and artistic research communities could greatly benefit from bridging the gap and opening a multi-perspectival discursive space for collaboration and exchange.

Several key research challenges in information visualization might be advanced by looking into strategies from other areas. An example is the improvement of the clarity of visual communication and the coherence of interaction models. Practitioners in the arts and design communities are confronting these issues but from different perspectives. Graphic designers have developed guidelines (related to modes of perception) for the use of type, form, and colour to optimize visual communication. Architects have used 3D visualization to aid in the design and conceptualization of space. Interaction designers and media artists are working in the digital domain, experimenting with animation, interactivity, 3D, and data visualization. Visualization design could tap into the ideas and experiments from the arts to help expand the repertoire of design strategies.

A common challenge in visualization design is the development of appropriate and comprehensible modes of abstracting and representing the complexity of information structures. An already explored strategy has been to use metaphors from other areas such as cartography or the natural environment (section 4.2.2). These metaphors are useful because they are structurally complex but universally familiar; users are familiar with the symbolic relationships between visual or interaction elements before they begin using the system. Cartographic style visualizations have been developed (i.e. *webmap.com*, *maps.map.net*) because users already know how to read the maps and can translate the spatial metaphor to an informational one. The natural and cultural environment is another excellent source of metaphors for abstracting complexity. It has over millions of years evolved robust ecological systems for the survival and adaptation of its elements.

To provide inspiration for dealing with these challenges, following is a selection of examples drawn from the domains of algorithmic art, architecture, computational complexity, and nature.

5.1.1 Algorithmic Art

An interactive visualization is an interface to a complex data space. Between the data layer and the graphic layer lies software code; the programming of algorithmic behaviours to map data into the visual domain. Increasingly visible on the internet, there is a growing community of interdisciplinary experimenters, often coming from universities or multimedia design studios, that are discussing visualization and the use of code for its construction.

This domain is sometimes referred to as "algorithmic" or "generative" art, other times considered a sub-specialty of interaction design. Practitioners use various programming platforms in which to experiment with creative modes of visual interaction. These include Macromedia Flash and Director (*www.macromedia.com*), in which web-based applications can be accessed by anyone with the free plugin software needed for viewing the content. Many visualizations are programmed in Java and viewable as applets in a web browser. An increasingly popular platform for coding Java applet visualizations is the non-proprietary "Processing" (*www.processing.org*), a visual sketchbook for digital artists. Other individuals are working with 3D graphics, producing real-time works in VRML or game engine environments (*udn.epicgames.com/Main/WebHome*) or non-interactive video work using ray tracing software (*www.povray.org*). There is a growing group of artists integrating creative visualization into live performance, using audiovisual processing environments such as Jitter (*www.cycling74.com*) or Keyworx (*www.keyworx.org*) to produce stunning visuals.

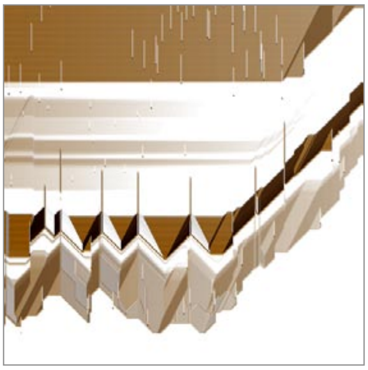
This is an exciting area for artistic experimentation; the possibilities of the technology are just beginning to be explored. An exhibition called "Abstraction Now" was held in Vienna in 2003 to exhibit the "current tendencies of non-representative art under special consideration of audio-visual media and interdisciplinary approaches" (*www.abstraction-now.at*). On this website there are links to many prominent algorithmic artists' and their work.

5.1 A–I ***Facing page.*** **Screenshots from artists working with the algorithmic generation of dynamic visuals.**

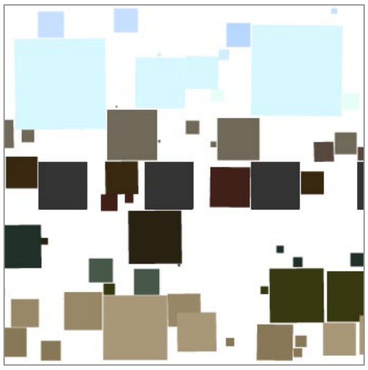
The following screenshots of artists' work provides a pointer and visual reference to individuals working in this area.

Yugo Nakamura
www.yugop.com

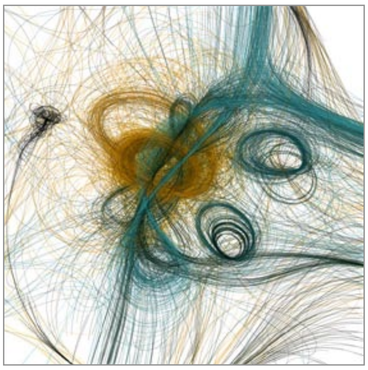
Lia
www.dextro.org



Jared Tarbell
www.levitated.net

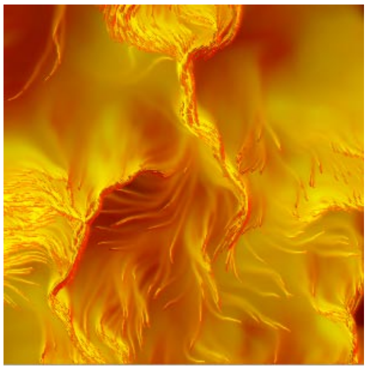


Casey Reas
www.groupc.net

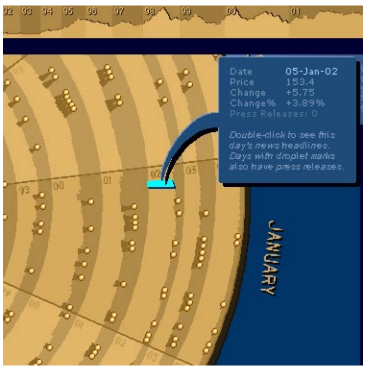


Marius Watz
www.evolutionzone.com

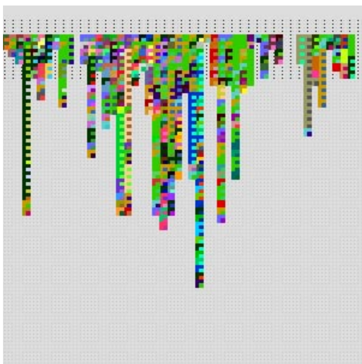
Robert Hodgin
www.flight404.com



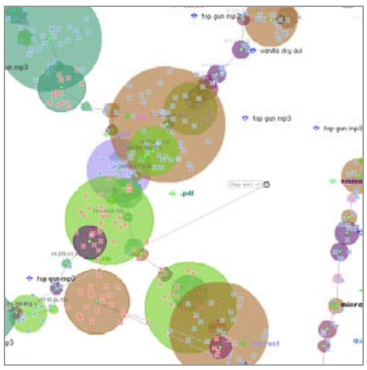
Golan Levin
www.flong.com



Lisa Jevbratt
www.jevbratt.com



Shoenerwisson
www.sw.ofcd.com



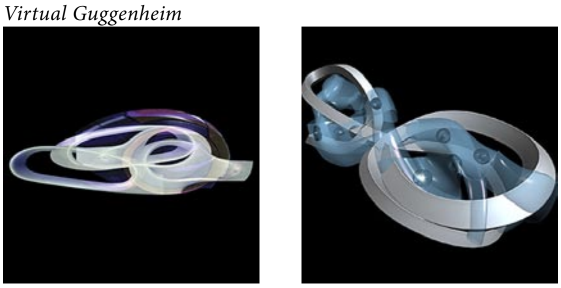
5.1.2 Architecture

Architecture deals with the construction and comprehension of space, and the facilitation of distinctive social behaviours in different spatial configurations. In the design process (as with information visualization), architects must be able to abstract, model, and represent these environments. This field has been transformed in recent years as digital technologies have given architects an entirely new medium for the conceptualization of spatial and material structures. Ideas for buildings can be simulated in 3D and tested before construction for use of innovative spatial paradigms and construction materials. Beyond gravity-bound architectural design, the incorporation of the virtual realm into architecture has encouraged the creation of concepts for theoretical hybrid structures that cannot (yet) be constructed. In addition, within the context of new media and information design, architects have developed some of the most innovative approaches to interaction in the mapping of spatial architectural principles to the information domain.

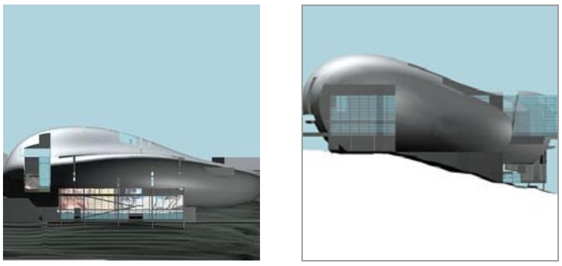
Some firms doing interesting work, often engaging digital technologies for design and visualization, include:

5.2 A-H A selection of architectural firms engaging digital technologies for design and visualization

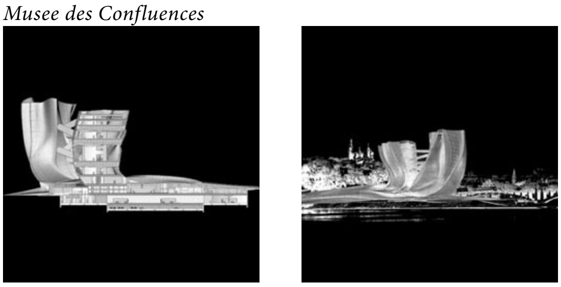
Asymptote
www.asymptote-architecture.com
Virtual Guggenheim



Morphosis
www.morphosis.net
Rensselaer Electronic Music Studio



Eisenman Architects
www.eisenmanarchitects.com
Musee des Confluences



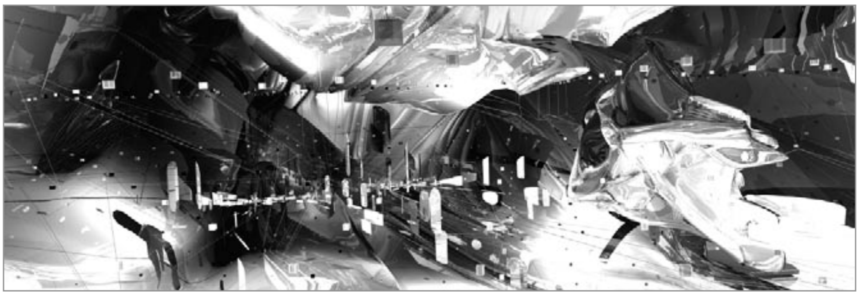
UN Studio
www.unstudio.com
Mercedes Benz Museum

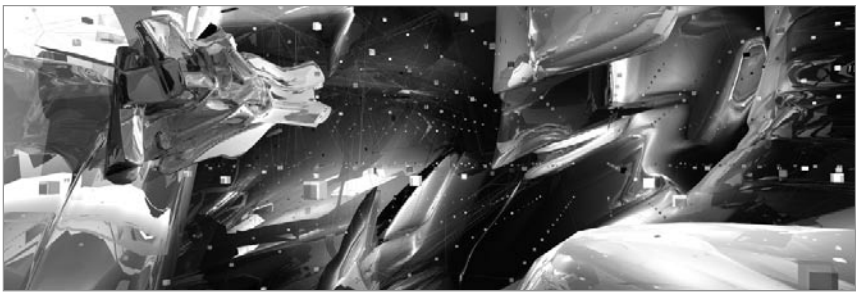
Reflexive Architecture

A community of visionary architects are employing digital technologies to explore "reflexive" architecture; the conceptualization of an intelligent and responsive space which is able to "*translate and connect to its contextual and environmental surroundings at a new level ... (not) grounded by the limitations of the present*" (Spiller 2002, back cover).

An example is artist/architect Marcos Novak, who researches the use of algorithms to create new architectural forms which he terms "liquid" architecture (*www.centrifuge.org/marcos*). While real-space architecture is limited to the constraints of physical Newtonian-Cartesian space, Novak builds virtual architectures that are void of the constraints of physical forms. Accompanying images are from the "ie4D" project, illustrating the notion of the liquidity of architectural forms (fig. 5.3).

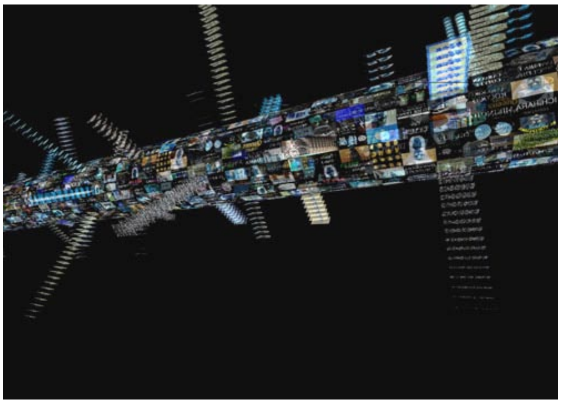
5.3 A-C Images from Marcos Novak's "ie4d" project.
www.centrifuge.org/marcos

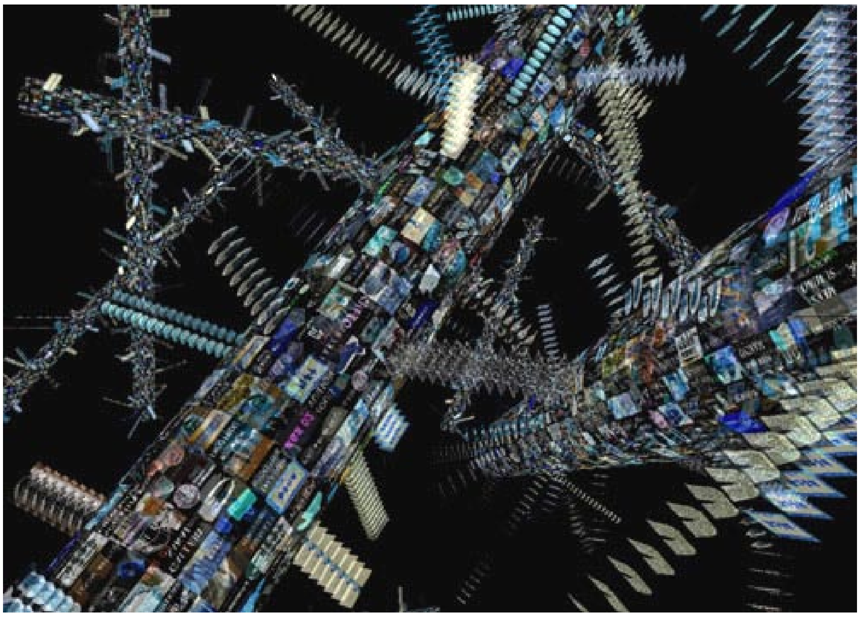




Information Spatialization

The architecture firm Plannet Architectures, led by Japanese architect Fumio Matsumoto, has experimented with the spatialization of information in virtual environments. They have produced several projects in which users navigate VRML interactive environments to browse information. An example is Infotube (*www.plannet-arch.com/information/tube.htm*) which is a virtual space to explore the relationship between urban window shopping and e-commerce product browsing. By projecting and translating the way products are spatially arranged in city shops into a virtual environment, the system provides a unique perspective on consumption (fig. 5.4).





5.4 A-C Screenshots from InfoTube.

www.plannet-arch.com/information/tube.htm

Other related projects:
www.plannet-arch.com (information architecture link)

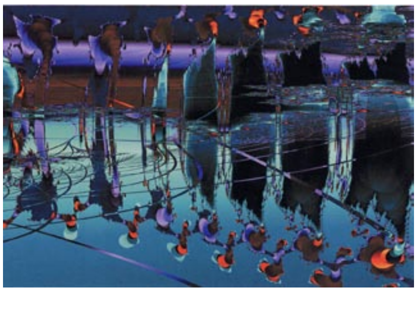
5.1.3 Computational Complexity

Within the scientific community, the use of computers has been widespread since the middle twentieth century to aid in calculation and simulation of complex phenomena. Computers are used by researchers in this context across the traditional divisions of science, mathematics, social science and art, and have provided a common platform for interdisciplinary research initiatives and experimentation. Examples of fields born out of this cross-disciplinary adaptation of computers to study complex phenomena include: artificial intelligence, artificial life, chaos theory, cybernetics, dynamical systems theory, emergent systems, fractal geometry, nanotechnology, and self-organizing systems (Wolfram 2002, 12). Harnessing digital computational power and the abstraction of complex phenomena into mathematical representation, researchers in these areas often use visualization to aid in interpreting complexity. Following is reference to two related examples: *evolutionary systems* and *cellular automata*.

Evolutionary Systems (Artificial Life)

Evolutionary computation lies at the crossroads between the study of systems of evolutionary biology and computer science (Bentley 2002, 9). By encoding genetic behaviours of ecological mutation into computer programs, it is possible to produce systems which simulate the properties of living ecosystems. An overlapping space between scientific and artistic practice, the artificial-life ("a-life") research community (*www.alife.org*, *www.generative.net*) is experimenting with the potential for the generation of new ideas and artistic products through simulation of evolutionary systems.

By harnessing the tendency of ecological systems to mutate in response to environmental conditions, complex visual environments have been produced. As featured in the book *Creative Evolutionary Systems* (Bentley 2002), projects have been done to implement genetic algorithms to synthesize images (fig. 5.5), music, virtual agents and virtual avatars. Applying properties of "organic" systems to information visualization (Fry 2000), sophisticated natural forms can be generalized and produce systems to encode and represent complex data.



5.5 A-B These images, produced in the late 1990's by Steven Rooke, were inspired by the work of evolutionary art pioneer Karl Sims (Bentley 131), and were produced using genetic algorithms.

image source:
Bentley 2002, plates 4-6

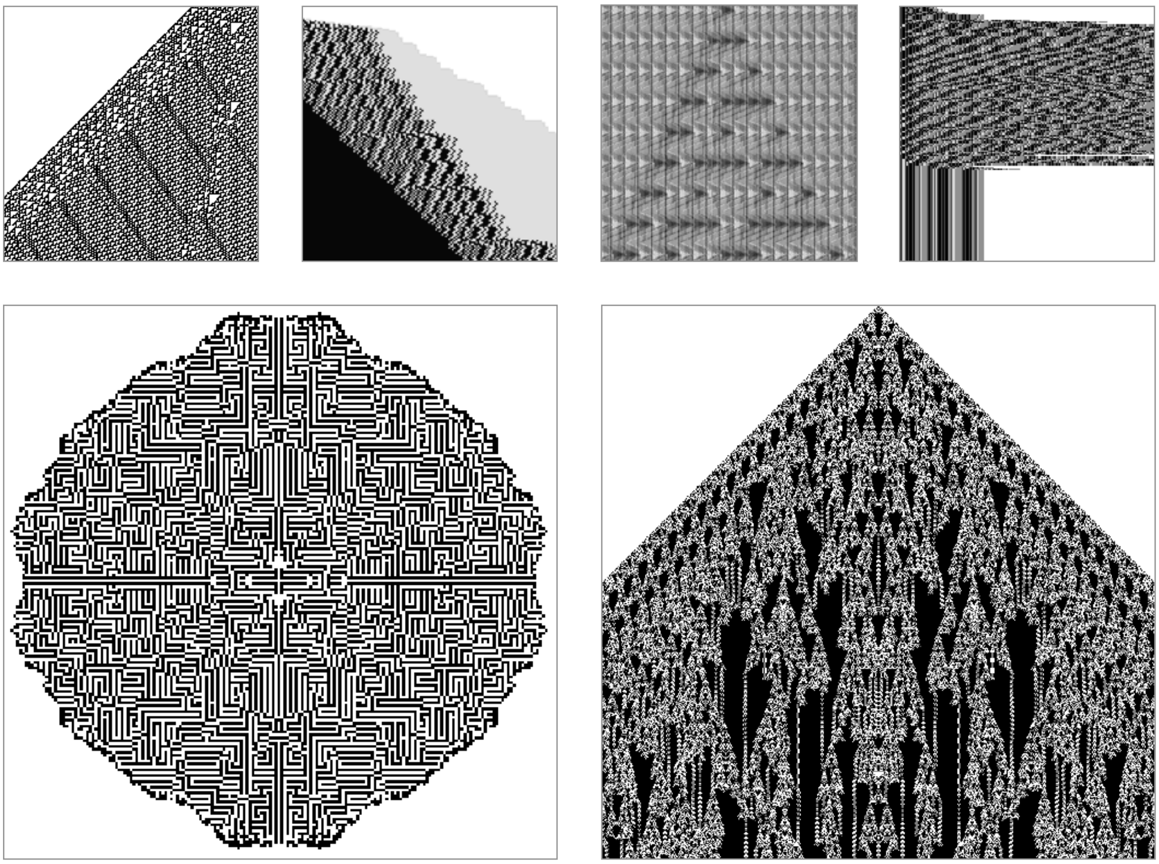
Cellular Automata

Stephen Wolfram is a physicist and mathematician, and developer of the Mathematica software. His recent (and ostentatiously titled) book "A New Kind of Science" (Wolfram 2002) explains the use of simple computer programs to set a framework for the understanding of complexity in nature. An example is the visualization of cellular automata to produce images which highlight regularities in complex systems. Cellular automata have been present in computer science discourse since the research of John von Neumann in the 1950's and popularized with J.H. Conway's Game of Life in 1970 (Wolfram 2002, 876). These are lattices of cells in which each cell has a particular state determined by the state of its neighbouring cells. The lattice configuration is given an initial parametrization and a set of rules and the states of the cells are determined step-by-step. These systems are allowed to evolve and are visualized to see patterns within the complex lattice. Below are images generated by cellular automata programs (fig. 5.6).

5.6 A-F Cellular automata based on different rule conditions

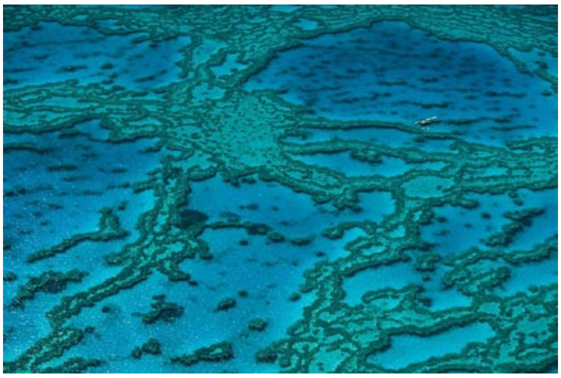
image source: www.wolframscience.com/nksx/screenshots

Cellular automata, as well as other approaches in computational complexity such as neural networks or parallel processing (Kohonen SOM maps, fig. 4.29), exhibit strategies for interpreting, encoding and visualizing complex systems.



5.1.4 Nature





The previous section on computational complexity highlighted a few examples of artificial systems that can be used for inspiration in visualization design. The most complex, dynamic, and adaptive system, however, is nature herself, and many ideas can be drawn from the ecological principles and visual characteristics of nature. The natural environment we inhabit has always been a source of inspiration to artists, documented since the earliest prehistoric cave drawings of Chauvet (Frankel 2002, 14). Nature's systems have evolved over billions of years to facilitate ecological survival through highly complex structures, processes, cycles, and flows. Trees, mountains, stars, rivers, flowers, insects, and moons exist in a subtle but complex equilibrium and provide an enormous wealth of inspiration for design (fig. 5.8).

5.7 A-H Images on the previous page:
The diversity of nature's ecosystems: forms, colours, and complexity.

Photography by Yann Arthus-Bertrand: ***www.yannarthusbertrand2.org***

Image locations (left to right, top to bottom):

1. Grand Prismatic Spring, Yellowstone National Park, Wyoming, United States.
2. Sandbank on the coast of Whitsunday Island, Queensland, Australia.
3. Marshes, Knifis (north of Laâyoune) ,Morocco.
4. Great Barrier Reef, Queensland, Australia.
5. Agricultural landscape between Al Massira dam and Rabat, Morocco.
6. Sebjet Aridal, near Boujdour, Western Sahara, Morocco.
7. Wooded island on a lake on Kenai Peninsula, Alaska, United States.
8. Buccaneer Archipelago West Kimberley, Australia.




5.8 A-D Images on this page:
Flowers exhibit nature's extraordinary diversity of design. They also display mathematical growth processes; as with the sunflower, whose seeds are patterned according to the Fibonacci series (Portoghesi, 432).

Image source:
Portoghesi 2000, 354-355, 432

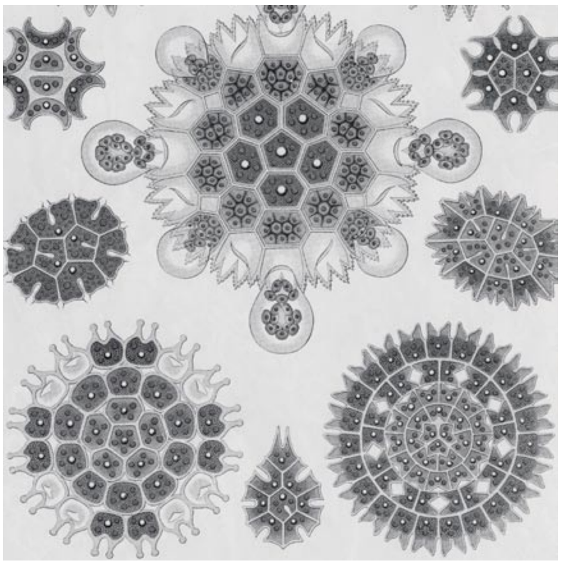
Nature has adapted through an evolutionary process and learned which designs function and which don't, and which systems are sustainable within their ecological context. Inventors, artists, engineers, and designers have always looked to nature for ideas; from the copying of beaver dams in dyke engineering to the mimicking of bird's wings to build an airplane. There is a growing movement in contemporary design and engineering practices (Benyus 1997) for the imitation of biological systems to solve human problems (such as food supply, energy generation, industrial production).

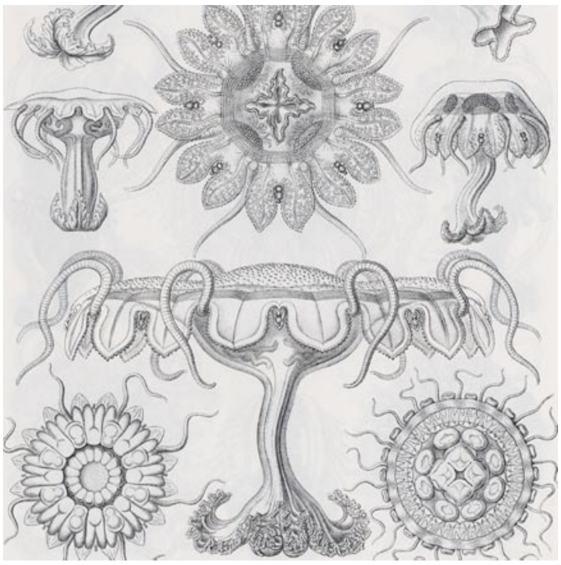
Examples of projects described in previous sections of this report which adapt or draw metaphor from nature:

*tree diagrams are used to illustrate hierarchies (*hyperbolic viewer)
*topographic landscapes show semantic context (*ThemeScape)
*a flowing river visualizes changes in data over time (*ThemeRiver)
*clouds provide a space for 3D data browsing (*V2 Datacloud2)

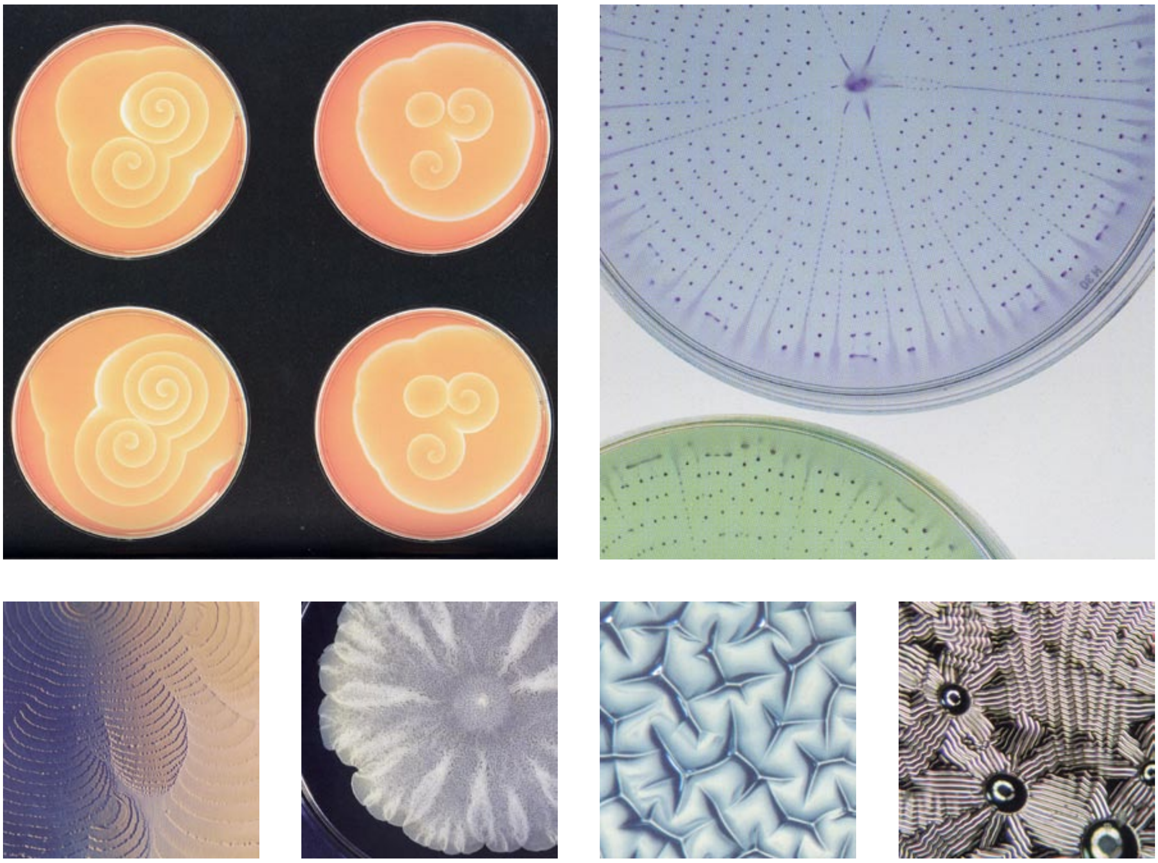
A superb presentation of natural objects which have complex and beautiful forms is Ernst Haeckel's book *Art Forms in Nature* (Haeckl 1974). Originally published in 1904, this is a renowned collection of illustrations of various living species. In hundreds of images of microscopic marine organisms and exotic plants and animals the diversity and beauty of nature is captured. In the search for new visualization metaphors, this book provides inspiration for the adaptation of complex geometric and graphic forms (fig. 5.9).

5.9 A-B Ernst Haeckel's drawings. On the left are species of algae and on the right are species of jellyfishes.
image source:
Haeckel 1974, plates 18 and 34





The book *Envisioning Science* by Felice Frankel is an instructional guide to techniques and aesthetics of presenting scientific phenomena with still photography (Frankel 2002). Frankel has a superb eye for the use of composition, lighting, focus, and presentation to optimally reveal the salient aspects of phenomena. The book is full of stunning micro- and macroscopic images of crystals, circuit components, liquids, and organic matter which are explained and analysed. One of the main messages of the book is that the attention placed on aesthetic quality is paramount in producing images which clearly communicate their message. Additionally, as with Haeckel's images, the perspective on natural objects shows their complexity and beauty, also providing a source of ideas for visualization design (fig. 5.10). The fractal architecture of natural systems is useful as a metaphor for the creation of zoomable interfaces which allow various perspectives and scales of detail on information. The pioneering work of Benoit Mandelbrot in fractal geometry and mathematics laid a foundation for this approach. Many visualizations use a fractal metaphor in the animated zooms into different levels of information (such as Vxinsight, fig. 4.32).



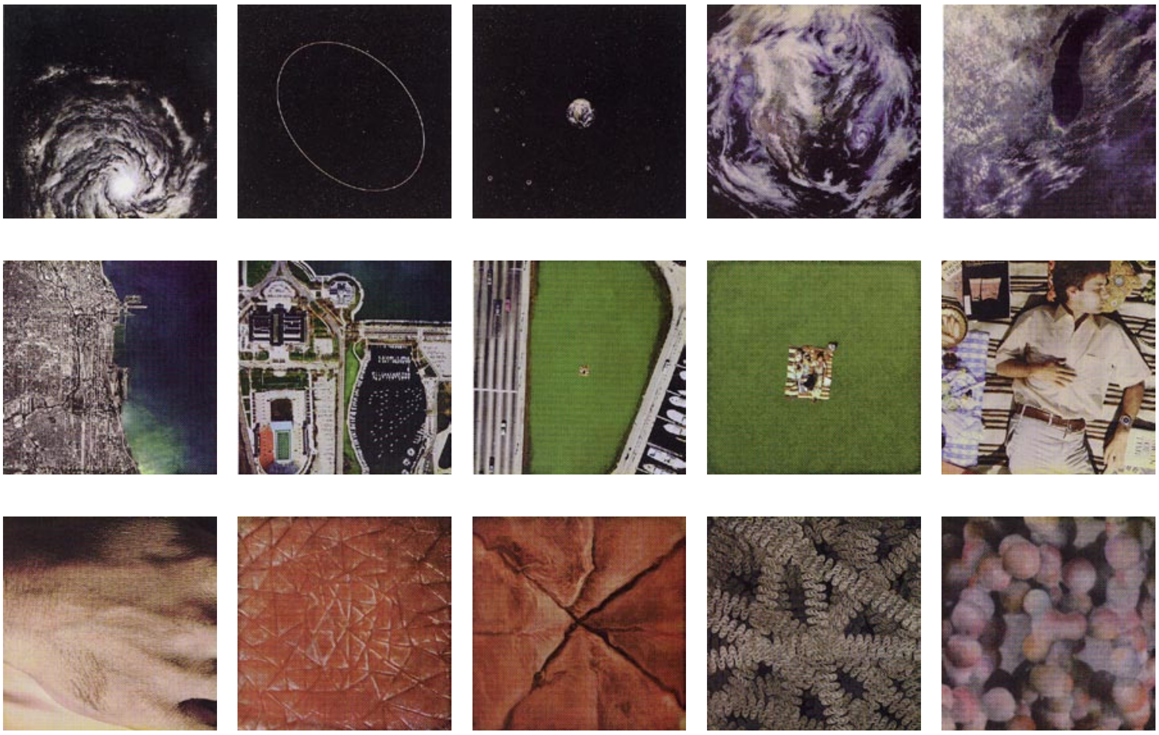
5.10 a-f **Felice Frankel's scientific photography**

source: **Frankel, 2002.**

Image contents and page numbers (left to right, top to bottom):

1. A sequence of images over time of the Belousav-Zhabotinsky reaction in a petri dish (138).
2. E.coli bacteria in petri dishes of various colours (119).
3. Proteus Mirabilis patterns under special light conditions (124).
4. Gold film buckled in a herringbone pattern (215).
5. A baker's yeast colony in a petri dish (110).
6. Surface patterns in an acrylimide gel (190).

In nature, complexity exists at various scales from the galactic to the atomic, as captured in these stills from the Ray and Charles Eames film *Powers of Ten*. A lunar view from outer space shows the earth's spherical surface and the dynamics of air, water, and land. From an airplane above a city we can see buildings and transport networks. Our own human eyes can see people and our interactions, trees, grass and animals. At a microscopic scale we can see the structure of cells and the architecture of crystal molecules. By presenting these images of scaled perspectives side-by-side as a sequence of images, the magnitude and complexity of our natural universe are revealed (fig. 5.11).



5.11 a-o A selection of stills from the Eames short film *Powers of Ten*. The sequence zooms in from left to right, starting on the top-left corner. The first image shows a view of the Milky Way galaxy from 10^{21} meters away from Earth. The last image shows human DNA nucleotides viewed from a distance of 10^{-9} meters.

image source:
Albrecht 1997, 110-111

The challenges facing information visualization researchers often involve finding innovative graphic and interactive techniques to represent the complexity of information structures. A great deal of research and experimentation with this same problem is occurring in other communities within the sciences, arts, or design.

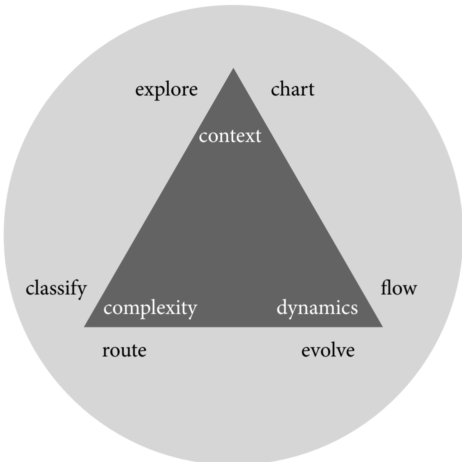
With the convergence and networking of media technology, there is the opportunity for greater interdisciplinary collaboration. By articulating common interests and increasing social exchange, shared research problems could be addressed in a multi-perspectival space and a broader cultural context. In the meantime at least, sparks for new ideas and solutions lie waiting to be discovered in the cross-disciplinary mutation of analytical and conceptual research approaches.

5.2 Summary of Survey Techniques

As a bridge from the previous examples for inspiration to the next section of principles, this section contains a summary (from systems in the survey) of techniques used for each meta-structure (*complexity, context, dynamics*). Looking at general trends in approaches to particular applications can contribute towards the definition of appropriate design strategies for each.

As a reminder of the survey classification system, following is the survey map, with meta-structures in the central triangle and sub-sections (i.e. applications) in the outer circle.

5.12 Survey matrix, as from figure 4.3.



Before summarizing each category individually, for interest's sake an assessment of the sizes of information spaces has been quantified by counting the number of information objects in the databases of each system. Qualitative descriptions of *small*, *medium* or *large* have been defined in relative terms based on the average number of information elements, documents, or nodes in the survey examples. The quantification of the number of objects in the survey examples was based on the following levels: small (1-30 objects), medium (30-100 objects), and large (100 to millions of objects). Counting the objects and averaging the results led to the findings presented in the following table (fig. 5.13), in which a general summary of each meta-structure is also included.

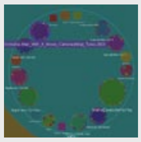
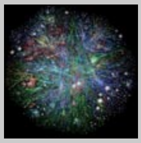
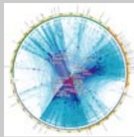
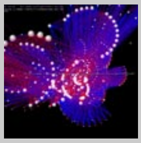
meta-structure	description	examples	dominant semiological elements	tendency for size of structure
complexity	paths, structure	tree, hierarchy, network	illustration of nodes and links	medium to large
context	relationships, content	object clustering	illustration of similarity and difference	small to medium
dynamics	movement, spatiotemporal changes	process diagrams arrows and vector fields	temporal axis, illustration of flow	small to large

5.13 Summary of survey sections, with properties and structure sizes.

The sizes are useful to acknowledge as the quantities factor into the scales that tend to be accommodated by each type of system. More specific properties and strategies for each meta-structure can be determined by looking at each of the three cases individually.

5.2.1 Complexity

The following table summarizes the techniques used to visualize *complexity*:

Meta-structure	Actions	Technique	Variations	Examples	Size	Visual structure
complexity	classify	fractals	interior	fractal circles, tree maps	medium to large	
			exterior (2D or 3D)	hiearchy tree hyperbolic viewer, visual thesaurus	medium to large	
	route	topology maps	cartesian coordinates	internet topology maps (Opte project)	large	
		spatial	polar coordinates (2D)	Skitter AS map	large	
			spherical coordinates (3D molecule metaphor)	WebTracer	large	

5.14 Table summarizing the techniques used in the survey examples to visualize *complexity*.

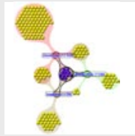
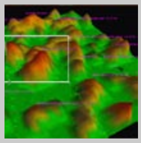
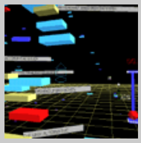
To reiterate the distinction between *classify* and *route* systems, the former are concerned with hierarchical relationships and the latter with the topology of information structures. Both of these systems are concerned with the complex paths through information spaces, but focus on different aspects of the architecture.

Classify systems often use fractal structures because, like fractals, they are composed *en-abîme* of self-similar sub-elements which are within or branch off of similar elements. The fractal can be set-up either as a tree with branches and sub-branches (i.e. *exterior* variation) or as a closed geometric shape (circle or square) with shapes and sub-subshapes within (i.e. *interior* variation). Both methods are useful to visualize small to large information spaces. The interior model is effective where quantity is concerned, as the size of the shapes are visually dominant. It also makes good use of the spatial real-estate of the screen by distributing the map in a spread. Colour is particularly useful as a distinguishing factor among the large quantity of on-screen elements (MarketMap, fig. 4.8). The exterior model more clearly displays the architecture of the fractal and enables the element-subelement relationships to be explored. A difficulty with these exterior systems is that it is necessary to distinguish elements with typographic labels, and these become unreadable if there are too many objects to be labelled. This problem of spatial density, however, can be overcome by extending the tree into 3D space (as with Munzner's hyperbolic tree, sec. 4.1.1). The strength of both models lies in their utilization of a *focus and context* display, in which both an overall view and more detailed look at individual system elements is simultaneously available.

Route systems tend to be useful for large information spaces such as the distribution of internet servers on a network or the potential paths in a hypertext. Due to the mass of data, these visualizations risk becoming overly dense and pushing the cognitive limits of the user. They usually do not intend to give a fine detailed view on individual elements but try to show patterns in an overall view. The use of polar coordinates (Skitter AS map, sec. 4.1.2) is particularly effective, as it clearly shows patterns in the density of radial lines. Cartesian coordinates maps (Opte, sec. 4.1.2) tend to illustrate that a space is complex, but often do not reveal trends in the data. The mapping of colour to some informational parameter (i.e. server location, bandwidth, etc.) is the best method to expose patterns, as the spider's web of nodes and links is too dense to read topologically. The extension of these maps into 3D (WebTracer, sec. 4.1.2) is more informative, as the opportunity to rotate around and obtain different perspectives on the space allows particular nodes to be explored in detail and reveals density of paths (i.e. WebTracer).

5.2.2 Context

The following table summarizes the techniques used to visualize *context*:

Meta-structure	Actions	Technique	Variations	Examples	Size	Visual structure
context	explore	clustering	overlapping zones	cluster map	small	
			magnetized pixels, search terms on surface	Kryphthästhesie, Sinnzeug	small	
	chart	spatial grouping	3D mountains	Vxinsight	medium	
			virtual environ-ment	VR-VIBE, Starwalker	medium	

Context systems, which give insight into the content of an information space and group objects based on semantic properties, are the most direct visualizations of ontological distinctions. The dominant mode of visualizing context involves spatially grouping objects into semantically differentiated clusters. The maps produced by these clusters are a great improvement over other modes of semantic presentation (i.e. lists) as they show two (or more) dimensional spatial relationships instead of one-dimensional linear relations. A great challenge in designing visualizations in which semantic knowledge structures (i.e. semantic networks) are revealed is illustrating that objects relate multi-dimensionally to other objects (assuming the ontology accounts for multi-dimensional relations and not just one-dimensional sorting). The Cluster Map (sec. 4.2.1) is a good example and is effective for a few search terms but becomes less readable as the number of

5.15 Table summarizing the techniques used in the survey examples to visualize *context*.

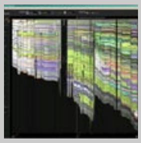
terms approaches ten. Modes of representing multi-dimensional relational networks which do not become messy and overly complex are yet to be developed. It is likely that the use of 3D space and multiple-perspectives can facilitate this complexity to be visualized and explored.

Explore systems visualize semantic content and allow the user the opportunity to explore the semantic space by interactively changing the spatial distribution of clusters. This is usually achieved by entering search terms directly onto the map (i.e. Sinnzeug, sec. 4.2.1), and these are often good examples of systems which integrate the interaction into the information exploration interface. By typing directly on the map and in some cases dragging and redistributing the clusters (Krypthästhesie, sec. 4.2.1), the user is empowered to interactively and intuitively determine the appearance of the map. Current interfaces tend to operate with relatively few information objects (i.e. small archives of less than 30 documents). As these systems develop more sophisticated modes of interactivity (use of animation, transparency, zoom, exposing different layers) they will be extended to larger information spaces. The intuitiveness of the interface and intimacy of direct manipulation of the information elements offer great potential, and explore systems are likely to be of significant value in navigating the future internet or digital archives.

Chart systems are similar to explore systems as they also show semantically grouped information objects, but do not allow the same degree of cartographic control to the user. The spatial distributions of semantic clusters are pre-generated from semantic analysis statistics and produce static environments. These interfaces tend to be useful for medium sized information spaces and make use of both spatial patterning (mountain ranges, grouped 3D glyphs) and colour and size to make multi-level distinctions. While the user does not have the freedom to interactively change the positions of clusters, the ability to navigate around or zoom in for different perspectives is common. Ideally, context visualizations will evolve into a hybrid of chart systems with high navigability and explore systems which allow dynamic generation of clusters.

5.2.3 Dynamics

The following table summarizes the techniques used to visualize dynamics:

Meta-structure	Actions	Technique	Variations	Examples	Size	Visual structure
dynamics	flow	vector fields	lines	Telegeography maps, SeeNet3D, NSFNet, Valence	medium to large	
			arrows	Bertin	medium	
		illustration		Susani social spaces	small	
	evolve	time axis	process diagram	Shedroff , Cuban missile crisis, beetle life cycle, music evolution	small	
			evolution diagram	ThemeRiver, History Flow, Revisionist	medium	
		sequence analysis	temporal	arc diagrams	medium	
			spatial	valence	medium to large	

5.16 Table summarizing the techniques used in the survey examples to visualize *dynamics*.

Dynamics systems are most concerned with the illustration of movement, flow, or change in time or space. The design challenge is to find appropriate modes of visually representing movement and change. Bertin's analysis of the use of arrows, lines, or vector fields (figure 4.35) is particularly useful with respect to static graphic elements from printed maps or charts. He explained the use of lines of varying thicknesses, colours, or textures to distinguish quantity of flow. His work needs to be reconsidered, however, for the digital medium which introduces the time dimension in the form of animation or dynamic visualization. Many of the survey examples make use of the same visual techniques that Bertin identified (Bertin 1974) but few have yet taken advantage of the digital medium to a great extent (with exception, perhaps, of Valence, sec. 4.3.1, which is an animated visualization).

Flow visualizations are dedicated to this challenge; the illustration of quantity, rate, and path of movement of some entity. Vector fields, including the tracing of paths along a map to indicate the route of flow, are the most common strategy and inherit largely from the static maps that Bertin analyzed. The examples included in the survey (i.e. Telegeography maps, NSFNet, SeeNet3D, , sec. 4.3.1) were static images generated from statistical data by the computer, but made little or no use of interactivity or animation. These maps are useful for visualizing medium to large information spaces, but by giving the user more control (i.e. filtering what is shown based on type, quantity, or location) and dynamically animating movement they could make them better simulations. The Susani illustrations of social spaces are not computer-generated but are simple hand-drawn illustrations to interpret social dynamics. These images are interesting as they are not mapped from data, but use an expressive artistic flair to represent the dynamics of social situations. There is great potential for visualization to manage complexity by making use of this strategy to communicate on both a denotative and connotative level of abstraction and representation (Schmidts 2004, discusses the explicit use of connotation as a strategy for the representation of complex spaces).

Evolve systems show the trail of influence or changes in a system over time. They usually make use of a temporal axis upon which processes, evolutions, or sequences can be assessed. By positioning elements along the time axis and mapping colour, size, or texture to parameters such as authorship, ownership, age, date, size, etc., interesting patterns are revealed. Most images are static (although some are generated by computer analysis) and offer little interactivity. The digital medium could be used effectively in the dynamic animation of temporal changes to reveal temporal patterns or trends. These systems have great potential to commercial applications such as medical or employment history, scientific or legal citations, learning aids to work processes, or analysis of political or historical events.

5.3 Principles for Knowledge Mapping

One of the initial motives of this research was to distil a model for the visualization of knowledge. It would be based on techniques used in current visualization systems, properties of knowledge, cognition and media and the dynamics of language and representation. After getting deeper into the problems, literature, and state-of-the-art in visualization research, this was realized to be an overly ambitious goal.

The mapping of knowledge is a complicated task, as problems arise in the representation, abstraction and translation of enormous complexity. The knowledge space (the dynamic interrelationships between human cognition, the representation of knowledge captured in documents, and the technology that supports its creation), has an organicity that rejects formalization. To date there is no theory of representation and interaction design which takes into account the imperceptible meta-structures of the knowledge space, the nature of cognition and perception, and social aspects of knowledge work.

Evolving strategies to organize (i.e. ontologies) and represent (i.e. visualization) the knowledge space will improve and may consequently facilitate the development of a formal visualization design theory. The models upon which this theory can be constructed, however, will have to find a balance between "formality" (objective, reductionist, explicit) and "essentiality" (subjective, wholistic, intuitive) (Nake, 3). A visualization is a representation, and a representation is always subject to the compromise between "*surface appearance and deep essence, or of explicit form and implicit content*" (Nake, 3).

This semiotic conflict, always an issue regarding the communication of knowledge via media, is brilliantly posed by René Magritte in his classic

5.17 Rene Magritte,
***La Trahison des Images* (1929)**
image source:
www.surrdave.com/images/pipe.jpg

1929 painting *La Trahison des Images*. Magritte's painting, as remarked by Michel Foucault (*Ceci n'est pas une pipe*, 1973), deals with the paradox of language and representation. It poses the problematic relationship between words and images, miring the viewer in the mystery of the message. Is the image a pipe, or not? It resembles a pipe, but the text claims it is not, perhaps because one cannot light it and smoke from it. Usually when viewing paintings or photographs, though, we accept the images of physical objects as objective views of the real thing. Magritte's painting brings to light the semiological paradox of representation, and the impossibility of objectivity and perfect clarity in the communication of a message.

Given the problems of representation inherent in knowledge, language, and media, the objectives of this research were changed from the development of a model from which visualizations could be designed to the elaboration of a set of guiding principles. Considered were factors such as the nature of knowledge, the strengths of human cognition and perception, and the social context of visualization use. Synthesizing these domains and the avoiding trying to deduce a universal model allowed a compromise between a "scientific" formalization, an "artistic" mode of trying to express the essence of a problem, and the limitations of design constraints.

It is possible that an elaborated design theory will evolve in coming years with continuing developments in visualization techniques and technologies, strategies for using the digital medium, and modes of analyzing, organizing, and representing the knowledge space. This would describe design processes, techniques, resources, and problems.

One of the great challenges in visualization design, however, is that there is no "ideal" visualization strategy; design is always application specific. Different systems are effective for different users of different backgrounds and needs (i.e. expert or novice, scientific or general information) and a universal model is difficult to generalize. With the difficulty inherent in providing general solutions to particular problems, offered instead are five principles which can provide a general foundation for design.

To generate general principles, then, it is necessary to consider the one element that is consistently required in the use of any system: the human mind. Systems should be designed to optimize the learning process by building on the strengths of the perceptual and cognitive systems. Current theories in perception, cognitive psychology, and the social applications of technology (section 2.1.2) can be factored to design for the optimization of cognitive resources. Extending perception and cognition from an individual level to a sociocultural level, the application of communication technology can be considered in a social context. Also, looking at properties of knowledge and how it emerges from information (sec. 2.1.3) offers a basis for knowledge (as opposed to info.) visualization design.

The following guidelines were derived from an analysis of the state-of-the-art in information visualization and from a synthesis of ideas in knowledge theory, cognitive psychology, perception, media theory, semiology, cartography, and information design. Much debt is owed as well to the extraordinary research of recent years in information visualization, interaction design, and the analytic techniques developed by information designers such as Jacques Bertin and Edward Tufte.

The principles for the design of knowledge visualizations are as follows:

1. *map*
   show patterns, not data
2. *optimize*
   maximize the information to cognitive effort ratio
3. *stabilize*
   stabilize the informational and operational context
4. *adapt*
   make the interface coherent with the application
5. *digitalize*
   push the potential of the digital medium to handle complexity

The five principles have been ordered based on their relation to psychological factors. There is a trend from the first through to the last in the relation to perception, then cognition, and finally socialization. The first principle, for example, builds on gestalt perception (the mind favours patterns over details); the second on cognition and perception in the limited processing capacity of these systems; the third relates to cognition in the support of active learning; the fourth relates to social cognition as it applies to the social application of the system; and the fifth to the socialization of the systems, as the refinement of digital techniques is a cultural process.

While these principles are useful in a contemporary design context, there are also allusions to desired properties of future systems which will not be subject to the same theoretical and technical constraints as those of today. The objective is to try to highlight some of the issues with current visualization systems and bring key design problems into the research discourse.

5.3.1 Principle 1: Map

map:
show patterns, not data

Otl Aicher, a German graphic designer active in the 1960's and 1970's, wrote a book called *analog und digital* (1991) in which he expounds the philosophical consequences of working with analog and digital media. A particularly potent example is the metaphor of an analog and a digital watch. These are both machines to tell time, but offer different perspectives by their differing modes of presentation (Aicher 1991, 45).

A digital watch gives a number; a precise (to the second or hundredth of a second) denotation of time. An analog watch, however, gives less precision (within a few minutes) but displays the time as the relative angles of hands. With each glance at an analog watch, the time is read both by what the angles of the hands are, but also by where they are not. At three o'clock the watch also shows the void of hands at nine or twelve or three o'clock. The different times of day and night are mapped out into a space of relative positions which, at the expense of precision, contextualizes the current time as a position (in the past, present, and future) in a twelve hour cycle.

This relation between precision and context relates to the distinction between data and information (fig. 2.7). Data are measurements, statistics, or numbers; information is an organized network of relations. It could be said that the precise time of a digital watch is data, while the contextualized time of an analog watch is information. Reading a digital watch demands extra mental calculation to figure out how much time has passed since the last time the watch was looked at. The analog watch displays this relation immediately just by observing the angle that the hour hand has rotated (which becomes instinctive after some experience). They are two unique modes of displaying the same information, but in one case the balance favours precision and in the other case it favours context.

5.18 A–B Digital and analog watch faces.

image source: members.tripod.com/Ben-Brandt/Photos

The task of a visualization, in particular when the communication of knowledge (as opposed to data) is at task, is to reveal context. The advantage of working in a visual space is that the map operates by showing what is as well as what is not; the differentiation of similarity and difference. Visualizations become effective when this potential to reveal context through visual and spatial patterns is exploited. Precise details about particular information objects should be available on demand (i.e. "details-on-demand"), but the overall context should be simultaneously maintained (i.e. "focus and context"). This requires the use of either multiple perspective windows (like in a 3D modelling software) or a single window with transparency, hyperbolic geometry or other strategy to show both overall and focused views on the information space.

Visualizations of small information spaces (such a pie charts or bar graphs, which usually illustrate measurements or statistics) operate at a level of reiterating precise data. Quantified numerical values are mapped directly to the size or proportion of some visual property. This is effective for small quantifiable sets of data and usually makes patterns easier to see than in lists or tables of numerical data. With larger and unquantifiable information spaces, however, such as digital archives or semantic networks, this direct translation doesn't necessarily expose patterns. These more complex information spaces require a deeper degree of interpretation and abstraction to be translated into the visual domain. Otherwise, visualizations can become too dense with precise visual details and become more of a cognitive drain than a cognitive aid.

The power of the visualization of a complex information space is the potential to discover the possible meanings of this space by exposing the meta-structures, rules, relationships, and associations that govern it. An illustratory example from the survey are the two internet topology maps, Opte and Skitter (fig. 4.14 and 4.15). The Opte map is a chaotic scattering of lines with unintelligible colour coding and offers little space for interpretation. It provides little insight into the properties of the servers, other than indicating the magnitude of the complexity of the data. The Skitter map, on the other hand, more clearly reveals information about the location of internet servers in the density of lines through the circle.

Due to the nature of digital technology, it can be difficult to take an "analog" approach to organizing information. Digital implementation techniques (such as database programming) tend to demand a precise definition and quantization of parameters and the alignment of information elements into discrete and inflexible structures. According to Shannon's information theory and the subsequent development of strategies to digitize analog signals, it has been necessary to force data elements into discrete quantizations. While this works for machine-to-machine signals, it has nothing to do with human thought or communication.

This technical constraint is reflected culturally in the "over-precision" of much of the information we work with. A travel itinerary printout from the train company, for example, might read: *train 4612 leaving at 16h56 from track 13 on May 18, 2004*. To someone a few hundred years ago they would not be able to process such detail and may say instead, "*I will travel early next week and should leave some time before lunch*". The over-precision of itineraries, invoices, and news reports, fill the cognitive environment with noise (i.e. data not information) and force the expenditure of much cognitive energy to filter needed information from unnecessary details.

The analysis and organization of information often tends to be precise and not relational due in part to the rigidity of ontological categories. One-dimensional ontological groupings (in which information objects can only be mapped to one category), such as those often used in contemporary databases, do not reflect the fluidity of the mind and the knowledge space. Improved ontological systems must be developed which account for the multi-dimensionality and complexity of semantic networks. The recent work of Pierre Lévy to map the "collective memory" (i.e. knowledge space) in cyberspace is a step in this direction (Lévy 2004b). The knowledge space is described as an "information ecosystem", and can be quantifiably mapped using a combinatorial system of tiny semantic units. The theory acknowledges that semantic networks are so complex that individual information elements cannot be located definitively, but only as a probability relation (thus the term "quantum semantics" - the metaphor is to Heisenberg's Uncertainty Principle, which revolutionized modern physics by stating the impossibility of knowing the exact position and velocity of an electron in its atomic orbit). This theory, or others like it, may provide a framework (as the longitude and latitude coordinate system did for cartography, developed by Mercator in the sixteenth century) for the mapping of semantic space and facilitate visualization design by making it easier to tap into particular meta-structures.

The use of digital technologies for knowledge work faces the contradiction between the fluid and abstract connections of the brain and the hard data of the computer. Some modern techniques, such as neural networks, attempt to overcome the rigidity of calculation by mimicking organic processes such as pattern recognition and "learning" through experience. But in general the majority of modes of working with computers demand a rigid and precise approach.

Visualization, as an abstractive and revelative view into an information space, has the potential to overcome these traditional restrictions. Data can be mapped denotatively in the visual domain, but it can also be twisted and stretched and interpreted to communicate at a connotative level. Visualizations can integrate interactivity with multimedia, exploit techniques developed in previous analog media (semiological play with collage or montage), and take codes from traditional cartography to open up a dynamic space for knowledge transfer.

Visual systems, especially with the development of appropriate design strategies and fluid ontologies, can expose relations in an information space that go beyond the obvious. Visualization can make the shift from simply a way of presenting information to a way of working with knowledge. Chaotic and random connections, like those that flow uninhibited in a creative mind, can be simulated and exposed on-screen. The user would be empowered to actively explore and experiment to discover the patterns and meanings from which knowledge is created. As expressed by pioneering computer scientist Richard W. Hamming in 1962, "*The purpose of computing is insight, not numbers*".

5.3.2 Principle 2: Optimize

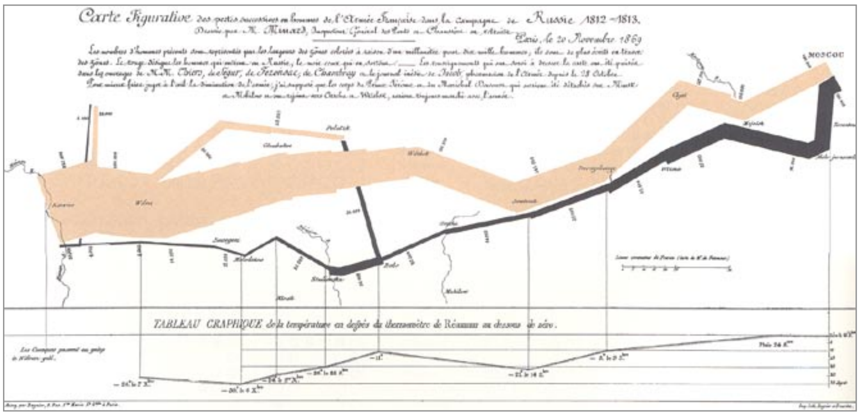
optimize:
maximize the information to cognitive effort ratio

Janine Benyus, in her book *Biomimicry* (1997), suggests that industrial design can learn from nature in finding creative solutions to conceptual problems, such as the use of a tree leaf structure as inspiration for the design of a solar cell. She summarizes the following rules by which organisms in a mature ecosystem are governed to enable survival over millions of years and through drastic changes in environmental conditions (Benyus 1997, 253):

> *gather and use energy efficiently*
> *optimize rather than maximize*
> *use materials sparingly*
> *don't draw down resources*
> *run on information*

Visualization design can benefit from the cut-throat lesson learned by natural organisms: optimize or die! The properties of natural systems apply to visualization in the context of the optimization of the cognitive potential of visualization users. Visualizations should be designed to transmit the maximum amount of information with the minimum cognitive exertion required.

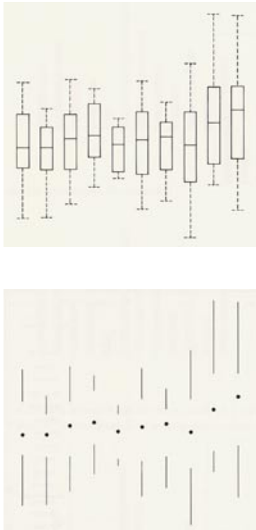
Every pixel on the screen should be justifiable and serve an informational or interactional purpose. Interaction with the system should be transparent (like a pencil, we forget about the technology and just use it), and it should follow the "grain" of cognitive flow. In an ideal optimization, on screen elements act as both interaction devices (buttons, scroll-bars) and information presentation (as with the Glass Engine, sec. 4.2.1). The visualization should be multivariate, simultaneously displaying variables such as size, quantity, relation, age, distance, semantic contents and structure, etc.



5.19 ***A figurative graphic of Napolean's march in Russia*** **by Charles Joseph Minard (1812-1813), a superb example of multivariancy. At least six variables are integrated: time, 2 dimensional location, temperature, number of men, and direction.**

***source*: Tufte 1983, 176**

These guidelines, which can be described as a "cognitive ecology" approach to the optimization of system and cognitive resources, are inspired by Edward Tufte's principles for the design of quantitative information graphics and the cognitive theory of learning (sec. 2.1.2). While Tufte generally concerns himself with static printed graphics and smaller information spaces (i.e. statistics or other quantifiable data), his ideas on "graphical excellence" (Tufte 1983, 51) nonetheless apply to interactive visualization of complex information spaces. Tufte's definition of graphical excellence includes the notion that a good design "*gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space*". Another principle is that "*complex ideas [should be] communicated with clarity, precision, and efficiency*". These guidelines, which support the optimization of cognitive resources, align with the notion of an ecological use of energy and materials.



5.20 A-B **Tufte's redesign of a parallel schematic plot. Both versions give the exact same statistical information, but the bottom example makes more efficient use of ink.**

***source*: Tufte 1983, 127**

Interestingly, it took a couple of centuries since the pioneers of information graphics (William Playfair, Charles Minard) presented their first bar graphs and pie charts until Tufte emerged with his principles. With the advent of the digital medium and the augmentation of complexity it introduces over static graphics, it is hoped that principles for the integration of interactivity, multimedia, dynamicism, and networked collaboration into visualization will not take as long to develop. In fact, Tufte's ideas about visual information, the "revelation of the complex" and optimization of data-ink ratio, are applicable to the realm of new media.

Tufte's optimization of visual elements can be extended to include the optimization of operational complexity and the support of cognitive flow. "Good" visualization design reveals the complex, but minimizes the cognitive effort required to see it. In more explicit terms, following are some example guidelines which could be adhered to for good design:

integration of interaction and information elements as much as possible

elimination of on-screen elements which don't serve a specific and useful informational or operational purpose

keeping both overall context and precise details readily available, perhaps faded into the background, in an adjacent window, or integrated directly into the map

use of intuitive interaction which supports and augments cognitive flow

smooth animation of on-screen elements, i.e. when adjusting scale, framing, or perspective

easy availability and variety of tools for scanning, browsing, searching, exploring (interaction types as per Canter, cited in Lango 2003, 40)

clean and readable typography, i.e. finding appropriate typeface, size, spacing, boldness, colour (for reference, try Forssman 1997)

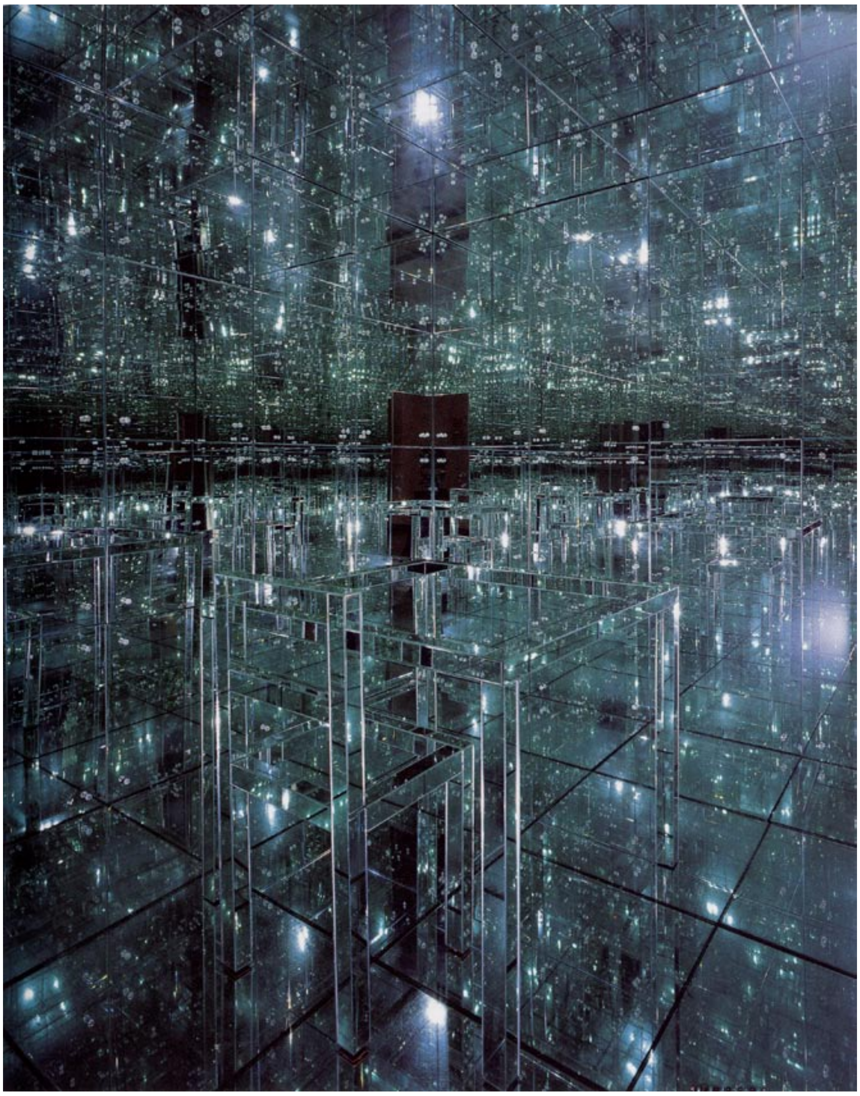
easily distinguishable colours and object sizes

This short list of suggestions fit the general principle of cognitive optimization. These guidelines help ensure that users of visualizations should be free to experience the knowledge space and not think about how to perform certain tasks or how the technology operates. Clarity in the operation and presentation of information supports clear seeing, working, and thinking.

The ideal application of visualization is to extend the power of cognitive processes by supporting analytic and creative thought. This can only be achieved if the simulation offered by the computer operates as a function of human needs, and not vice versa. Current digital technologies (hardware and software) force humans to operate the machine on its terms, often constraining creative output to the capabilities of software tools. As the trend of improvements to software and hardware design continues, and interfaces become optimized for workflow efficiency, visualization may achieve its potential to empower human cognition.

5.3.3 Principle 3: Stabilize

stabilize:
stabilize the informational and operational context



5.21 ***Mirrored Room*, Lucas Samaras (1966). Albright-Knox Art Gallery, Buffalo**

image source:
Stafford, Barbara Maria, and Frances Terpak. *Devices of Wonder: From the World in a Box to Images on a Screen*. Los Angeles, USA: Getty Publications, 2001, p263

A walk through a hall of mirrors at an amusement park, a maze of hallways with glass or mirrored walls, is a strange experience. One's image can be seen reflected on surfaces in every direction, giving the sense of being displaced from the body. The amusement of the experience comes from the confusion and loss of stability that comes from the uncontrollable dispersion of one's image into the surroundings. But this experience, like others at the amusement park, is only fun because the loss of stability is anticipated and controlled. If an earthquake should cause the floors of one's home to wobble, on the other hand, the loss of stability would cause fear and anxiety. It is taken for granted that a building has stable walls and floors, strong enough to withstand inclement weather.

The *information anxiety* often experienced today in our navigation through information space occurs in part due to a similar reason to the anxiety caused by a wobbling floor: lack of stability. In this case it is the stability of the informational and operational context which is not maintained. Bytes of information (from newspapers, books, magazines, tv, radio, internet) are presented out of context and with unnecessary precision, and our interfaces to the information are often confusing to operate.

Visualization is one mode to overcome this information anxiety by extracting and presenting key details and patterns, but only if it offers a *stable* foundation to the user. A principle for the development of visualizations is that they ensure that the information presented is organized and contextualized in terms of who, what, when, where and how it was produced. Operational stability, the use of an intuitive and consistent graphic layout and interaction language, also optimizes the user experience.

Lack of informational context is what renders much of the "valuable" information on the internet into useless unordered data. The search results from the Google search engine, for example, are presented as a long list of hits. Scanning this list, no sense is given of the context of the information. A Google search would be quicker and more reliable if there was an option to modify a search or the order of returned results based on the following questions: Who produced the content? What are the sources of information? Where is the author located? When was the content produced? What is the scope of relevance of the site? Is it academic, commercial, personal, entertainment, journalistic, artistic, or governmental? Is it mainly text, image, or sound, or all combined? Is it for expert, intermediate, or novice experiential backgrounds? Is the content free or is a registration or fee required to access it? Has the content been approved for quality or reliability by an editorial committee? These questions, if addressed, increase the "information richness" or learning capacity of information (Daft & Lengel, cited in Panteli 2001) by facilitating a more efficient cognitive integration.

“*Data becomes information only in context of a desire, need or purpose*” (Scotti 2004). Information presented out of context (as with Google) is data if it does not relate to the user’s need and thus carries little meaning. Visualization, by offering many more dimensions with which to map parameters (3D space, colours, sizes, shapes, etc.) than a one-dimensional list, will be able to provide users with freedom to search and view results based on more desired parameters, thereby increasing the informational context.

The current problem of chaotic, unorganized information will likely be addressed by future generations of the internet. The semantic web will make use of XML metadata tags to contextualize web data (Berners-Lee 1998). Beyond that, fluid ontologies will likely enable a more flexible “quantum semantics” (Lévy 2004b) which will contextualize data into a multi-dimensional network of descriptions and associations. These modes of analysing and organizing data before it is presented will deepen contextual stability and make the information space more manageable, thereby improving visualization systems.

Visualization, in particular, should (both now and in the future) ensure that information is presented with as strong a contextual foundation as possible. Firstly, this requires the empowerment of the user to choose what information is displayed in order to satisfy his/her needs. Secondly, multivariate mapping of visual parameters to informational parameters gives as many (user-defined) details in as readable a map as possible. In a cluster map spread of a digital archive (i.e. Sinnzeug or Krypthästhesie, figures 4.19 and 4.20), for example, the following mappings could be done: colour to the degree of multimediality, on-screen location to semantic relevance, object size to reliability of the source, brightness to cost, transparency to the date of production, and texture to the level of background expertise required. Thus several dimensions of information can be integrated into a visualization, not even considering extra dimensions possible through additional interactivity, animation, and multiple perspectives.

In addition to informational stability provided by visual elements, consistency of the operational interface is of key importance. Objects, tools and processes for working in the system should be clearly and consistently represented. Design thus requires a sensibility to graphic and information design, and an understanding of the perceptive and cognitive processes a user requires to learn and operate the system. Use of colour, type, arrangement and balance of visual elements should encourage easy navigation and orientation. Like the signs and icons that guide travellers through the maze of halls in an airport, the buttons, icons, menus, tools, and processes required to operate the system should facilitate intuitive operation. The objective is not to crowd the interface; the use of on-screen whitespace allows a user to breathe and differentiate visual elements with less mental effort. Consistency at different degrees of scale is also key; the language of presentation and interaction need not change when zooming from a view of millions of documents to that of just a few.

Attention should be paid to the optimal balance between the complexity of the visuals and interaction and the limitations of the cognitive system. Good design is the revelation of informational complexity through as usable an interface as is possible, as stated by Edward Tufte (Tufte 1983, 191):

> *"What is to be sought in designs for the display of information is the clear portrayal of complexity. Not the complication of the simple; rather the task of the designer is to give visual access to the subtle and the difficult - that is, the revelation of the complex."*

Tufte's comments on visual information design apply to interaction, which should offer the maximum functionality with a minimum operational difficulty. To keep the interface at an optimal complexity, the user could have the opportunity to interactively toggle the visibility of different information layers and dynamically reduce the number of variables displayed.

The contextualization of information objects occurs by the presentation of data as a multi-dimensional function of its position in a semantic network. This, in addition to the optimization of interface's usability, provides a foundation for the stabilization of knowledge work environments.

5.3.4 Principle 4: Adapt

adapt:
make the interface coherent with the application

Knowledge is context dependent, and it is useful in a particular application. For example, Robinson Crusoe's (from Daniel Defoe's 1719 novel about a shipwreck survivor's adaptation to live on a deserted island) knowledge on how to build a shelter from tree branches would not be very useful to someone wanting to use a computer to write an email. With this in mind, the design of knowledge systems should be optimized for the context of their use or application. If a scientist wants to find out how an idea developed by tracking research citations over time, than the system should be designed to illustrate these evolutionary patterns, and not clutter the presentation with undesired details, such as the locations or educational backgrounds of the researchers. Visualization is an abstraction of the information, and this abstraction should be performed to maximize the display of desired information and minimize distractions or noise.

5.22 a-b Harry Beck's 1933 London Underground map on the left. A geographical map of the same tube system (as it is today) on the right.

image sources:
Left: *tube.tfl.gov.uk/content/history/map.asp*
Right: *www.kordy.dircon.co.uk/misc/alt-map.gif*

The London Underground Tube map is a famous example of a design which is optimized to its application. Released after years of research by Harry Beck in 1933, the map abstracted the geographical curves and distances of the railroad network into a colour-coded grid of horizontal, vertical, and diagonal lines. The stations are shown to be evenly spaced along straight railroad lines. If the same information is instead mapped according to geographic proportions, a different picture is painted; lines snake around physical landmarks and the stations are unevenly spaced.

The gridded Beck map abstracts the geographical space and presents the space in a form which is coherent with the information an individual wants to obtain from the map. A Tube rider wants to know how to get from one stop to another, how many stops are in between, where to change lines, and in which direction to travel. The rider is underground and is detached from the geographic space, she just has to make sure that she gets off at the correct stop and makes the right connections. These particular concerns are more readily addressed by the Beck map than the geographic map. There are limitations, however, to Beck's mode of presentation. It is more difficult to assess the geographic distances that must be travelled in a particular journey. In certain shorter trips, for example, it may be quicker (and cheaper) to walk than to take the Tube. Someone who has lived in London for some years and has experience with the spatial topology of the city could make this assessment based on experience, but the Tube map would not be of great help. This decision would be better facilitated by the geographic map. However, in the majority of situations the most important information that a Tube rider needs are obtained more readily using Beck's map. As Beck described the reasoning behind his abstraction, "*(it) seemed common sense. If you're going underground, why do you need bother about geography? It's not so important. Connections are the thing*" (Hadlaw 2003, quoting from Ken Garland's conversations with Beck). The Beck map is extremely useful in its particular context of use and is considered a classic of information design.

As illustrated by the Beck example, visualization designers should be consciously aware of what details are most desired by the user and ensure that the information space is abstracted to emphasize this information. They should also tune into the meta-structures (rules, relationships, associations) that govern the information space, and build the system to reveal them. Systems should be arranged in terms of visual, spatial and interactivity elements in order to align to the particular application and dominant meta-structures of the information. At best, the interface itself becomes "transparent" by seamlessly integrating into the information space that is being explored (i.e. Glass Engine, sec. 4.2.1).

For an information space, there are three dominant perspectives that the user can be given: topology (*complexity*), content (*context*), or changes (*dynamics*). Design tends to require a compromise between each these three; one can be clearly illustrated only at the expense of the others. The Beck map, assessed from this perspective, favours topological "paths" (i.e. *complexity*) over geographical "content" (i.e. *context*).

The three main perspectives, or "meta-structures", reflected in the categorization of examples for the survey, are based on the primary action or insight that the system gives the user into the information space. An initial assessment in the design process is to decide which meta-structure would be most important to the user in using the system. Once this decision is made, the visualization system can be designed in terms of which aspects of the information should be most revealed. Some ideas of which particular techniques would be appropriate for particular applications can be inferred from summary of survey techniques above (section 5.2).

It is probable that, in the coming years, sophisticated visual and interactive techniques will be invented which will allow *complexity*, *context* and *dynamics* to be visualized in a single system. These designs will likely be facilitated by an established repertoire of visual and interactive techniques for given visualization contexts, and, unlike today, will not have to be built ad hoc from trial-and-error.

As visualization becomes more commonly utilized as a discursive format (taking advantage of the digital medium, as literary discourse takes advantage of print), there may evolve a visual language which enables a communication of ideas and discoveries. A visual language, with a defined grammar and syntax, would provide a structure which could support the revelation of particular meta-structures. This visual language would grow out of the heritage of visual art and knowledge representations, from ancient ideographic systems to the modern work of twentieth century design theorists (such as Kandinsky, Klee, Kepes, Neurath).

Wasily Kandinsky's work is particularly relevant as a foundation for the development of a visual language through his work with abstraction. He worked to describe "*an explicit grammar for a visual language*" (Holtzman 1995, 84) by experimenting with form, composition, and colour. Defining the basic elements of visual language as colours, points, lines, and planes, he analysed how these elements interacted to produce rhythms, harmonies, and spiritual vibrations. Kandinsky "*believed that abstraction was the pictorial language of the future, that it communicated truths about the human spirit that were beyond the reach of traditional, figurative art*" (Whitford cited in Bond 1999). While Kandinsky's vision for the potential of a visual language has not been entirely realized, visualization can certainly learn from his techniques and approach to visual expression.

5.23 A–B Wassily Kandinsky experiments with abstract forms. He believed that abstraction was the "*pictorial language of the future*".

A visual language, with a defined grammar and syntax, would provide a structure which could support the revelation of particular meta-structures in knowledge visualization.

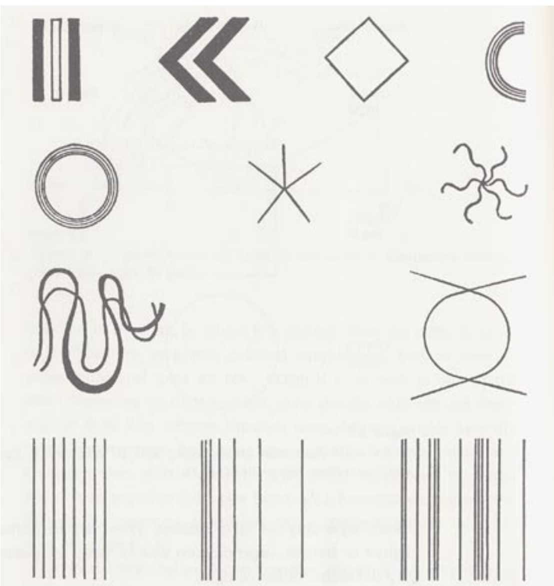
Left: *Some simple examples of rhythm and repetition* from Kandinsky's *Point and Line to a Plane*, figures 50-58 & 59-61.

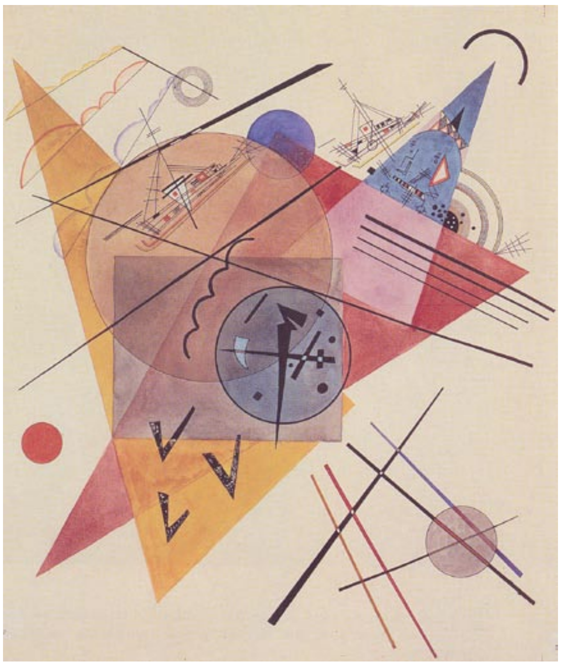
***Right*: *Dream Motion* (1923) © Solomon R. Guggenheim Foundation, New York**

***image sources*: Holtzman 1995, 82.**

Through the systematic application of visual strategies in mapping knowledge this visual language will develop and be of great benefit to designers. Once the major needs and backgrounds of the users has been determined, information can be appropriately abstracted to the visual domain by making use of the expressive possibilities of the visual language. As this language develops, in addition to advanced interactive and analytical techniques, visualization systems can be more readily customized to their context of use.

In the meantime designers can use whatever techniques they have at their disposal, but should ensure that the system is optimized for its use and that the most important information (paths, content, change) is the most readily revealed.



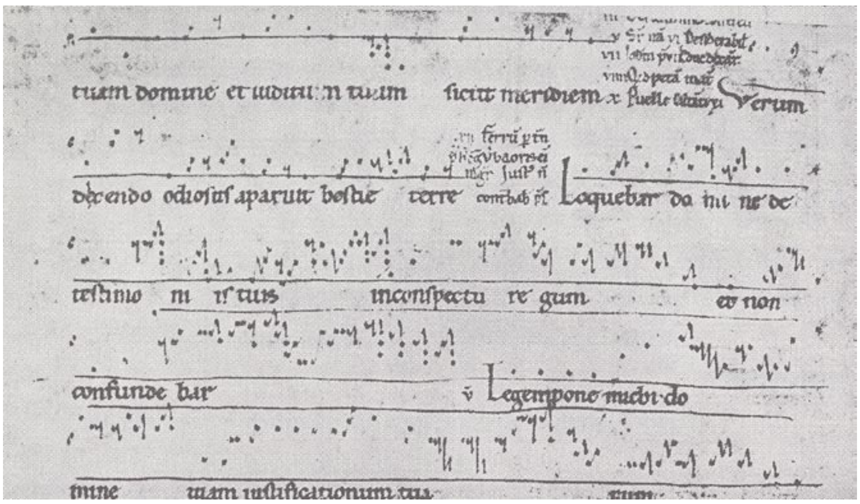


5.3.5 Principle 5: Digitalize

digitalize:
push the potential of the digital medium to handle complexity

The knowledge space is extraordinarily and increasingly complex (sec. 2.2.1). A couple of hundred years ago, books and speech were the major media in which knowledge was stored or transmitted. The advent of industrially reproducible and electronic media (photography, telephony, radio, television) and now digital media has produced a exponential increase in the complexity of the knowledge space. Books, photographs, radio programs, films, spreadsheets, websites, and emails capture knowledge from domains of medicine, ecology, art, government, and economics, just to name a few. A problem is that with so much information distributed in so many media forms, current modes of managing this knowledge space are proving insufficient. It is extremely difficult to find the right information at the right time, or even to keep track of what is known and what is not.

One reason for this is that modes or "technologies" of knowledge work have hit a "complexity barrier". The term "complexity barrier" has been used by Jefferey Long (1995) to define the limit of the communicative potential of notational systems (i.e. alphabets or Arabic numerals). Notational systems are technologies of representation, and by their nature they support the complexity of a discourse up to a certain point before becoming insufficient. They act as a "cognitive lens", to use Long's term, constraining the communication of knowledge to their expressive capabilities.



An example is music notation, which has developed since the time of the ancient Greeks (Holtzman 1995, 15). Early notations from the seventh to fourteenth centuries used *neumes* to approximately indicate the form of a melody. This was useful for charting the rising and falling of Gregorian chants, for example. The next few centuries saw the emergence of today's standard notation, in the use of lines, circles and other symbols to precisely indicate pitch and duration. This notational system enabled Mozart, Bach, and Beethoven to capture their musical genius for all history. In the twen-

5.24 A–D As music and its discourse have evolved, so has its notation.

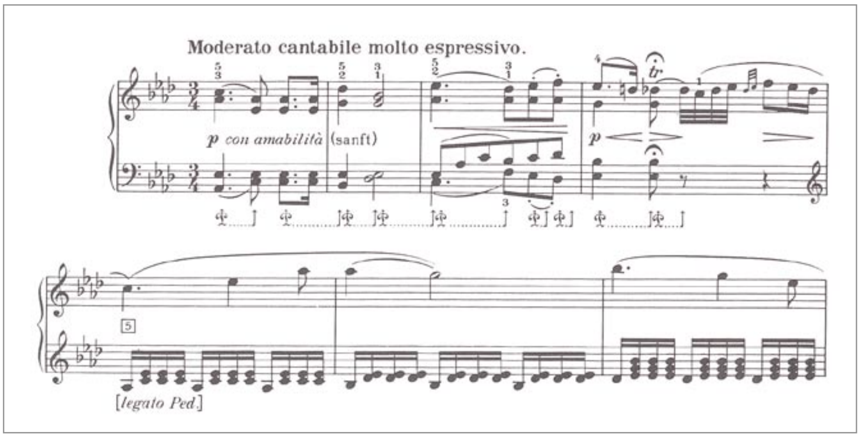
Left: Chants notated with *neumes* from a twelfth century manuscript.

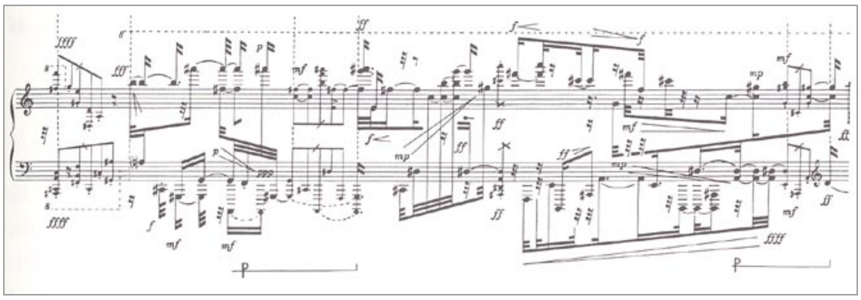
Top right: Beethoven's *Piano Sonata in A flat opus 110* from the nineteenth century

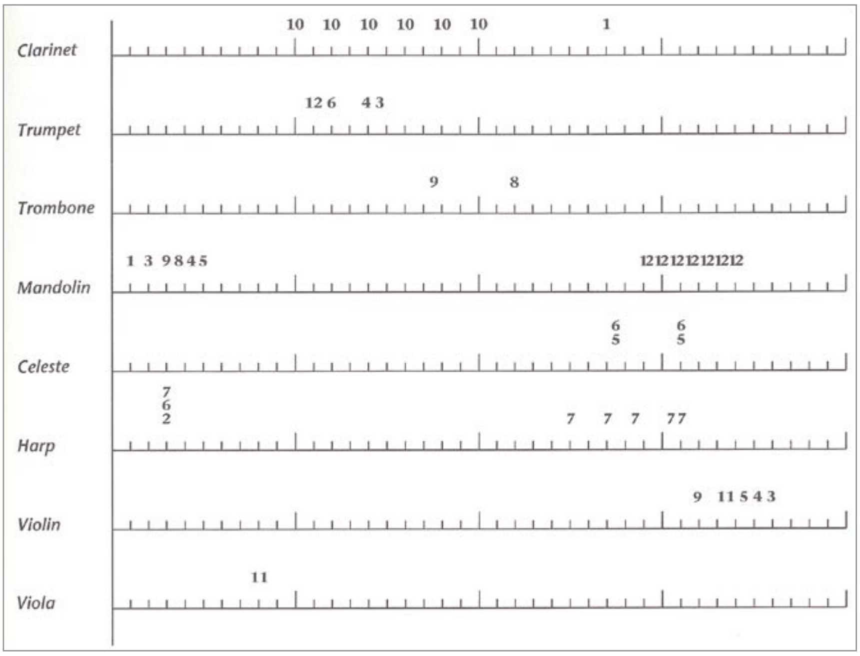
Middle right: Karlheinz Stockhausen's *Klavierstück VIII* from the twentieth century

Bottom right: Transcript from a section of Anton Webern's *Five Pieces for Orchestra*.

***image sources*: Holtzman 1995, 16 & 65**







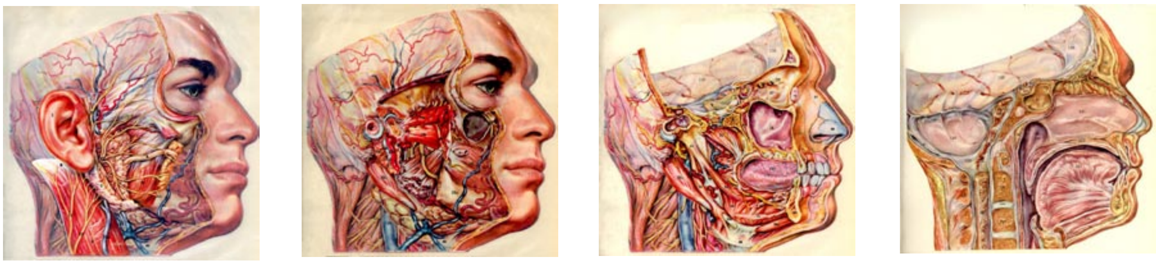
tieth century, in particular within the avant-garde, composers required a completely different notation to communicate more precisely how a piece should be played (such as the Webern score on the previous page). The clicks, samples, and soundscapes of today's computer-based electroacoustic music cannot be notated at all. From this brief history of music it is evident that composers have required an increasingly sophisticated notation (or *communication technology*) as they wanted to express more subtle, precise, and complex information.

The same is true for the knowledge space; it has become more complex and thus requires more subtle and precise modes of managing and communicating within it. While the digital medium has already facilitated an increasing placelessness and weightlessness of information, most modes of organization and representation have been inherited from older forms of media. This has historically always been the case, that new media inherit the forms of older media, but it also occurs that after a gestation period the new media emerge with their own distinctive language (McLuhan 1964, 8).

The *language* of digital media, with its own semiotic and semantic forms, will be grounded upon its unique characteristics: interactivity, dynamicism, networkability, and multimedia. Each of these characteristics adds a layer of complexity to modes of signification in established media. For visualization to come into its own as a notational system and form of communication, it will have to make full utilization of the digital medium in which it exists.

The new space of signification opened up by digital media is facilitated by the dynamics of the new medium and is accompanied by most radical complexification of the media sphere since the introduction of the alphabet, paper, or books. The ironic twist is that the increase in complexity of media, which correlates to an increase in complexity of the knowledge space, can facilitate a reduction in the complexity of modes of interfacing the knowledge space. This occurs through the reduction of cognitive effort required to work in an information space through the use of well-designed organizational and operational interfaces. Visualizations become effective when they turn the digital media's tendency to complexity into an efficient mode of managing that complexity; using the fire of the dragon to tame the dragon. Current visualization systems are a step in this direction, but will only become powerful simulational, representational, and observational mechanisms upon further development of digital technology and techniques.

Current visualization systems tend to dominantly display either paths, content or change (as indicated by the survey categories). While unique views into a system should maintain these perspectives, with full exploitation of the full potential of the digital medium systems will be able to be interactively shifted from one meta-structure to another. It is likely that in the future, systems will offer the user extensive freedom to decide how and what they see on-screen. Like with children's anatomy books, in which layered transparencies showing the skeletal, muscular, and internal organ systems can be viewed all together or one at a time, users should be able to toggle the visibility of different information layers (fig. 5.25). In this increased user flexibility to filter through different informational densities and perspectives, the potential of visualization to be a window into highly complex information spaces can be realized.



5.25 Layered images of the auditory system and structures of the head

images source:
***The Human Ear in Anatomical Transparencies* (1946), by S. Polyak, G. McHugh, and D. Judd**
www.rcsullivan.com/www/sonotone/sonframoo.htm

A fundamental change from traditional cartography to digital visualization is the increased *power* of the user to participate dynamically in the mapping process. The fundamental tasks of the traditional cartographer to set-up and codify the map (scale, framing, selection, and coding; see section 3.2.2) are now within the user's control. These cartographic elements can be controlled by interactive operations such as zooming, dragging the centre of view, filtering visibility of certain information, and toggling definitions of visual elements. A good example of a current system which hints at the potential of interactivity in future systems is the on-line map and route-finder *www.map24.com*.

Many of the visualization examples in the survey enable user interaction of dragging, zooming, filtering, and toggling. The interaction paradigms, however, often do not allow a fluid and intuitive integration of these interactivity elements. Problems relate to both technological constraints and unrefined design; they include stuttered animation, unpredictable behaviour of visual elements, lack of integration of tools into a coherent toolset, and the lack of customizability or filterability of the visual elements. Some years of research and experimentation are yet required to refine strategies for the coherent integration of interactivity to fully empower the user in their work.

Unlike paper, the computer screen can animate visual parameters. The dynamism of the computer screen can be taken advantage of in the flexibility of such elements as size, colour, form, texture, transparency, brightness, density, and direction. An application of the manipulation of these visual elements includes the use of transparency, fade, tint or blur to filter out the overall context from the current view. Adjusting the values of these parameters gives the visualization designer the ability to take advantage of gestalt perception to direct the user's attention while dividing the visual field.

Designing visual on-screen parameters for gestalt perception (Zwimpfer 1994) includes the clustering of pixels or the use of figure-ground to distinguish a focus area from the larger overview (which could be placed in the background). An application is the Krypthästhesie visualization (figure 4.19), which uses bold black lines for the foreground and faded grey lines for the background. Netzspannung's Semantic Map (fig. 4.21) pulls related elements into a large circle which is half-transparent, keeping the background of the map fully visible. The Glass Engine (fig. 4.24) makes the active interaction elements more visible by making the active toolbar blue and reducing the others to dim white notches. These uses of colour and transparency to make a figure-ground distinction allow the overall context to be maintained but not draw away from the focus area. These mappings and manipulations of visual and animation elements make up the semiological foundations for a visualization system.

Future visualization systems will push the potential of both visual and interactive design, and of the digital medium in general. Visualization, as the digital medium, is still in its infancy, and will greatly develop in coming years. Today's researchers, however, including scientists, artists, engineers and designers, are already experimenting with many of the techniques that will likely characterize visualization:

3D graphics and navigable virtual environments

fluid animation and embedded multimedia

real-time updating to data fed over the network

collaborative environments, enabling researchers in different locations to work together

a coherent repertoire of tools for probing, searching, filtering, toggling, and changing perspective

modes for simultaneously displaying overall context and precise details

non mouse-keyboard interfaces (i.e. physical controls or motion sensors)

Through the systematic implementation of these techniques, designers and users will develop the *language* of the digital medium. Visualization, as the interface between cognition and computation, is likely to become a significant contributor to the realization of this language. Systems will be customizable to users of different skills and background levels, and be adaptable to different contexts of use. They will employ a coherent and intuitive set of tools which will require little extra cognitive effort to use, as a pencil is used to write without thinking about how to use it or how it works. Visualizations will give insight into the meta-structures that govern complex systems and be *windows* into the knowledge space. They will be systems of notation and representation and explorable reflections of human culture and cognitive activity.

6 Conclusion

Designers of knowledge visualizations could greatly benefit from a comprehensive theory to establish a foundation for the conception, implementation, and assessment of systems. This thesis proposes a framework for such a theory through its exploration of key issues: how knowledge emerges from information; the strengths and limitations of cognition and perception; the social context of knowledge work; the roots, language, and problems of visual knowledge; modes and metaphors for mapping complex abstract information; and the state-of-the-art in current visualization practice.

An integration of concepts from these areas was facilitated by the description of three dominant meta-structures that can be revealed in a visualization: *complexity* (paths), *context* (relationships), and *dynamics* (change). Subsequent analysis facilitated the distillation of the following key principles, which could be applied, mutated and refined to eventually form part of the theoretical basis from which visualization design can be approached:

> *map* - show patterns, not data
> *optimize* - maximize the information to cognitive effort ratio
> *stabilize* - stabilize the informational and operational context
> *adapt* - make the interface coherent with the application
> *digitalize* - push the potential of the digital medium to handle complexity

With an acknowledgement of these principles and an interdisciplinary awareness of strategies for effective design (i.e. from interaction design, graphic design, typography, cartography, and cognitive psychology), it is likely that visualization will increase its potential as a medium for knowledge communication.

Assuming the continuation of improvements to technology and design theory, the increasing utilization of visualization could have a significant cultural impact. The power of visualization to augment cognition, and its potential to make transparent the flows and activities of the knowledge space, could change the nature of communication and discourse. With the continuing cultural integration of visual media (from printed illustration to photography and film), there is a historical trend for literary discourse to be supported by a visual discourse. As described by art historian Barbara Stafford (Stafford 1996, 23):

> *"The history of the general move toward visualization thus has broad intellectual and practical implications for the conduct and the theory of the humanities, the physical and biological sciences, and the social sciences - indeed, for all forms of education, top to bottom."*

Designers would play a significant role in the coordination (technical, conceptual, and aesthetic) of this discourse by conceiving and implementing visualization systems. In the words of information design pioneer Gui Bonsiepe, an advocate for the potential of a "viscourse" (i.e. visual discourse) (Bonsiepe 1997a, 5):

> *"Design theory could be brought to bear fruitfully in investigating the links between visuality and discursivity. Then words would be brought to images, and images to words; discursive intelligence and visual intelligence would be brought together."*

But the refinement of a useful design theory will require research and development in several key areas, many of which were alluded to in the body of this thesis. Firstly, more robust visualization algorithms and an improved technical infrastructure to support the organization and transfer of knowledge. Secondly, interaction and graphic design that complements the strengths and limitations of the cognitive and perceptual systems. Thirdly, improved modes and metaphors for the abstraction, organization, and representation of highly complex knowledge spaces. Fourthly, the refinement of a visual language and its augmentation by the utilization of other senses, such as hearing and touch. And finally, a better understanding of the language of the digital medium and effective modes of taking advantage of it.

This thesis research was able to gather and integrate some of these key problems that should be addressed to work towards a design theory. However, the ideas and principles proposed can only be refined by being empirically tested in practical application; the logical next step in this research would be the application of these concepts to the design of real visual systems. The journey towards the fulfilment of the quest for knowledge visualization will be taken in small steps, and a comprehensive design theory will evolve through the experience of which designs are effective and which aren't.

To conclude, it should be clarified that the embracement of visualization for communication should be taken with caution. Notwithstanding the potential of visualization to expose relationships and phenomena in the knowledge space which may otherwise remain unobservable, it is limited by the semiological constraints of representation. While visualization can support and extend cognition, aspects of the original perceived space are lost and a new reality is presented. This is, however, no substitute for the unmediated human experience of intimate personal presence in some time or place. In the words of Moby Dick author Herman Melville, "*It is not down on any map, the true places never are.*"

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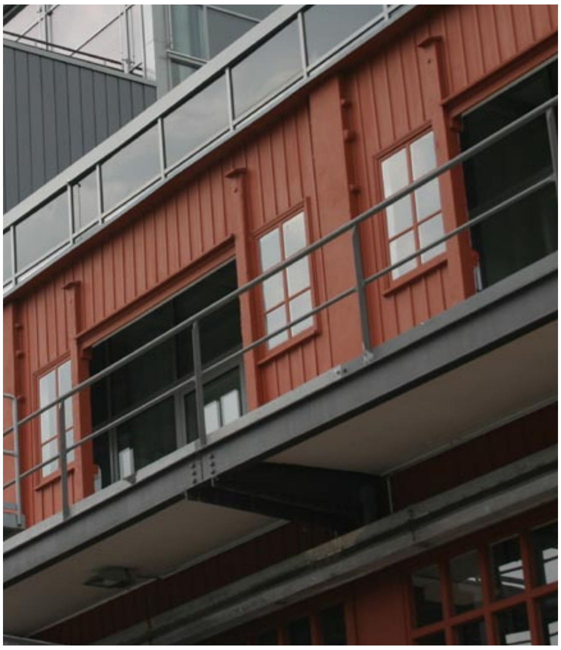

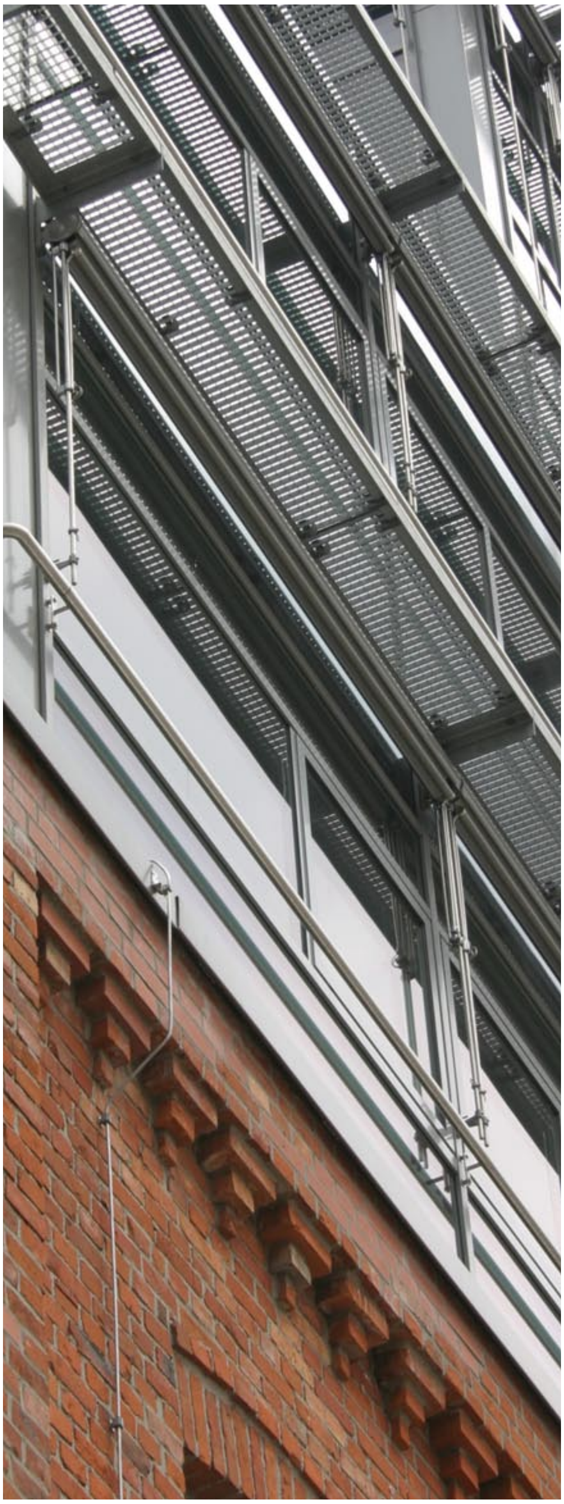

Thanks to the International School of New Media, the ISNM, for providing the environment and inspiration which helped make this work possible.

As part of the first graduating class, I wish much success for the school, faculty and students in the coming years.