VISUALIZATION OF CLINICAL PRACTICE GUIDELINES

AND PATIENT CARE PROCESS

By

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ABSTRACT

This dissertation proposes a visualization system that supports clinical knowledge evolution procedure–development, use, evaluation, and dissemination. The visualization encodes essential patient care steps into visuals and also seamlessly incorporates patient records, clinical documentation, imaging archives, and decision-making aids into the visuals. The system addresses current problems of inconsistent clinical interpretation among medical practitioners and inconsistent use of evidence-based medical practice because the verbal description is inherently limited in illustrating procedures and associated decision logics. The visualization enables clinicians to recognize past history of patient care process, practice clinical knowledge, and envision the prospective care process more efficiently. The research work in this paper modeled the knowledge evolution cycle using clinical guidelines (CPG) in a format of medical logic module (MLM). The tree structure of clinical decision logics, based in MLM, is visualized in a hyperbolic geometry to best meet the criteria while making the visual representation more useful in the context of clinical use. The interaction in the visualization is designed to support development, use, evaluation, and dissemination of CPGs. Considering the visualization as a clinical decision aid evaluating patient care options, the design visually encodes quantitative or qualitative information in concert with the tree visualization. In conclusion, the proposed visualization enables medical practitioners to visually understand clinical knowledge, organize patient care process, and evaluate the process in a unified abstract representation.

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CHAPTER 1 INTRODUCTION

Sharing clinical knowledge has been increasingly emphasized to improve health care quality. For example, HL7 (Health Level Seven) [5,6] is an international community of healthcare subject matter experts and information scientists collaborating to create standards for the exchange, management, and integration of electronic healthcare information. HL7 promotes the use of such standards within and among healthcare organizations to increase the effectiveness and efficiency of healthcare delivery for the benefit of all. The knowledge is to be shared among the different local clinical settings such as in medical schools and hospitals. Seamless adaptation of the knowledge, one form of which is represented by *clinical practice guidelines* (CPG) [10], is critically important to provide good patient care. A clinical practice guideline presents a logical diagnostic and treatment sequence to help discern the optimal process among care options for a clinical situation, trying to comprehensibly cover all eventualities. This enables care-givers to reduce medical errors by avoiding errors of omission of critical care tasks, while also promoting improved quality of care by facilitating rapid application of appropriate diagnostic and treatment modalities. Unfortunately, the combination of the complexity of a comprehensive CPG and variability of clinical presentation can make the use of CPG difficult in the clinical setting. Poor representation of the knowledge can result in improper interpretation, suboptimal practice, and omitted essential care process.

1.1 Motivation

Currently, more attention has been paid to the need to share CPG among disparate information systems than how to present the CPG to care-givers. While it is felt that successful adaptation of CPG into local settings is necessary for widespread use of CPG [10-12], there is no widely accepted form or visualization tool for using guidelines. Thus, the various representations of a guideline or variations between guidelines, are a barrier to clinical usability. Ideally, the guideline representation should be uniform and independent of the guidelines or local settings. To address these issues, it is necessary to examine how clinical practice guidelines are utilized from the users' point of view in an effort to externalize the "thinking processes" of organizing patient care tasks.

1.2 Problem Domain

The creation of a new knowledge representation to aid this "thinking process" resolves around two key concepts: 1.details of care tasks, and 2.contextual view of how those tasks are related. The former details the tasks or intermediate outcomes of the tasks, while the latter is more concerned with the context underlying reasoning associated with each task. Narrative verbal statements type of CPG found in use currently does not successfully meet the requirements, because described task-by-task and the underlying decision logic and associated care process are not clearly disclosed by the narrative format.

For example, when a doctor starts diagnosis of a patient, the doctor observes symptom(s) and brings his or her clinical knowledge (rules) to differential diagnosis from which subsequent diagnostic and treatment activities are initiated. Using a guideline, these activities become tasks in clinical workflow. The two main parts of the patient care process representation are the important branch points in the decision structure and the streamlining of actual clinical practice chosen among the various possible sequences in the knowledge. As imaging representations have been used to represent complex knowledge in many other domains [13-15], such a visualization approach could address the two essential components of the CPG process. In addition to the improvement in actual clinical practice, the visual representation would also facilitate the enhancement of clinical learning in medical education, and provide a more accessible method to educate patients in order to obtain their participation in the decision making process [16]. The use of the visualization would be also a useful tool in the clinical review process [10], thus enhancing overall health care quality.

CPG coverage is quite wide and a guideline usually covers various possible cases for an observed symptom. Use of same CPG may result in many different patient care processes. The representation should consider not only better understanding of CPG but also better usage in patient care process making medical practitioners retain the understanding well. The original CPG representation should not be much different from the representation of patient care process using the CPG. The two should be comparable and in a unified concept.

Comparison between patient care process and CPG or between two patient care processes can serve as a tool for enhancing an existing guideline or analyzing care process. This can hardly be achieved by conventional representation of CPG or patient care process. The better comparison tool helps medical practitioners observe the process of how the CPG is adapted to a patient case. The enhanced usage of CPG by resolving the current representation issues and providing medical practitioners with a flexible interactive tool can promote the use of CPG.

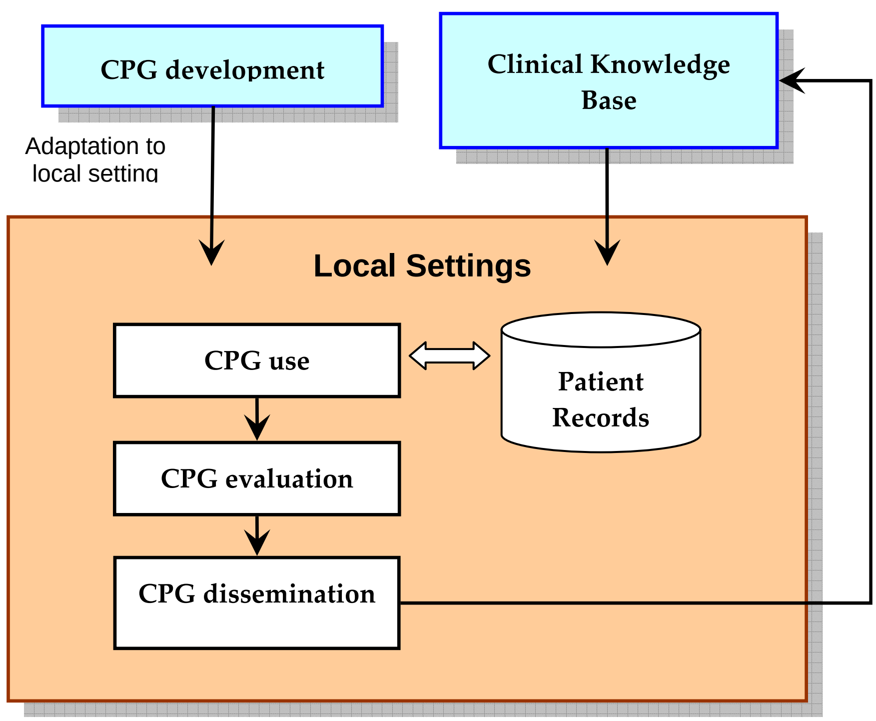


Figure1.1 Illustration of CPG evolution cycle

1.3 Proposed Solution

In this dissertation, a novel visualization system is proposed that systematically visualizes clinical practice guidelines, using these clinical knowledge concepts. An example of its application in planning care process is developed to demonstrate how it can influence the decision making process. It is an interactive visualization system that conforms to a unified abstract of the underlying knowledge derived from the clinical knowledge evolution cycle of CPG creation, usage, and evaluation (See Figure1.1). Modifying a well established graph drawing algorithm, hyperbolic tree drawing [17], the visualization places visual metaphors designed to represent CPG primitives and the relationship between them. This visualization enables medical practitioners to visually organize and understand the overall clinical care process including clinical decision making, thereby promoting more and better use of CPG.

1.4 Original Contribution

This dissertation describes the work believed to be original and contributory in the following aspects.

Clinical knowledge in the form of CPG is visualized and the proposed visualization system in this dissertation solved a problem of representing the complex and large scale visual structure of patient care process. The novel visualization gives medical practitioners a tool with which they can organize tasks in patient care process and understand underlying logics and decision making. Design criteria and associated visualization solutions are studied based on the clinical knowledge engineering and visual knowledge discovery methods. A tree visualization algorithm is modified and adapted to represent clinical knowledge. User interaction for note taking, easy authoring of CPG, and navigation of CPG are designed to achieve plausible interactive rate.

Decision support visualization is also combined with the CPG visualization. This enables users to not only explore logics but also capture additional information related with the logics, such as decision scores or significance values for involved tasks. The capability benefits understanding both the decision logics and the significance of each of care options.

The work described in this dissertation has already resulted in the two reviewed publications [7,8].

1.5 Document Organization

Chapter 2 reviews various works in CPG representation and implementation, scientific/information visualization, visual knowledge discovery, and graph visualization and knowledge representation.

Chapter 3 discusses criteria for visualization of CPG structure. It lists problems when we use the visualization as just projecting CPG structures to visuals. It also includes important paradigm for the visualization and accommodation of some useful concepts in visualization.

Chapter 4 describes Focus+Context concept [13,14,18] and how graph visualization has come up with the concept. Hyperbolic tree visualization [17,19], one of Focus+Context graph visualizations [2], is explained.

Chapter 5 explains basic CPG authoring and navigation by hyperbolic tree visualization. This chapter especially devotes to explaining the modification of the basic hyperbolic tree visualization and addition of tools incorporating clinical data details.

Chapter 6 describes a clinical decision making and how the visualization supports the decision making process. Significance value for each task is discussed and how the values appear and the distribution of the values over the tree visualization gives attention to decision makers.

Chapter 7 describes the system based on the criteria in the previous chapters and presents results-example usages. Chapter 8 concludes the dissertation and presents potential future research.

CHAPTER 2 PREVIOUS WORK

2.1 Clinical Practice Guidelines

Clinical practice guidelines are defined by Institute of Medicine [10] as “systematically developed statements to assist practitioners and patient decisions about appropriate healthcare for specific clinical circumstances.” Health organizations have developed the guidelines and promoted the use of CPG to improve health care quality. A part of an example guideline is shown in the Figure 2.1 [3]. As seen in the figure, guideline includes narrative statements of definition, history, diagnosis, and wide range of resources for a symptom. Tables, diagrams of protocols, and figures are often included to describe clinical process. Guidelines and various CPG formats have been developed and published from several different sources.

Although CPG do not have to be computer-based, the use of computers brings many benefits such as integration into hospital information system or decision support system and, thus, has become an essential component of CPG. Following sections will discuss how computer based approaches have addressed the issues of representing CPG.

2.2 CPG format

II. DIAGNOSIS

A. History and Physical

Recommendation

Class I

In patients presenting with chest pain, a detailed symptom history, focused physical examination, and directed risk-factor assessment should be performed. With this information, the clinician should estimate the probability of significant CAD (i.e., low, intermediate, or high). ***(Level of Evidence: B)***

1. Definition of Angina

Angina is a clinical syndrome characterized by discomfort in the chest, jaw, shoulder, back, or arm. It is typically aggravated by exertion or emotional stress and relieved by nitroglycerin. Angina usually occurs in patients with CAD involving at least one large epicardial artery. However, angina can also occur in persons with valvular heart disease, hypertrophic cardiomyopathy, and uncontrolled hypertension. It can be present in patients with normal coronary arteries and myocardial ischemia related to spasm or endothelial dysfunction. Angina is also a symptom in patients with noncardiac conditions of the esophagus, chest wall, or lungs. Once cardiac causes have been excluded, the management of patients with these noncardiac conditions is outside the scope of these guidelines.

2. Clinical Evaluation of Patients With Chest Pain

History

The clinical examination is the most important step in the evaluation of the patient with chest pain, allowing the clini-

Figure 2.1 An example of clinical practice guideline [3]

To facilitate computer utilization in CPG, there have been standardization efforts involving formalized clinical knowledge and clinical decision making in medical

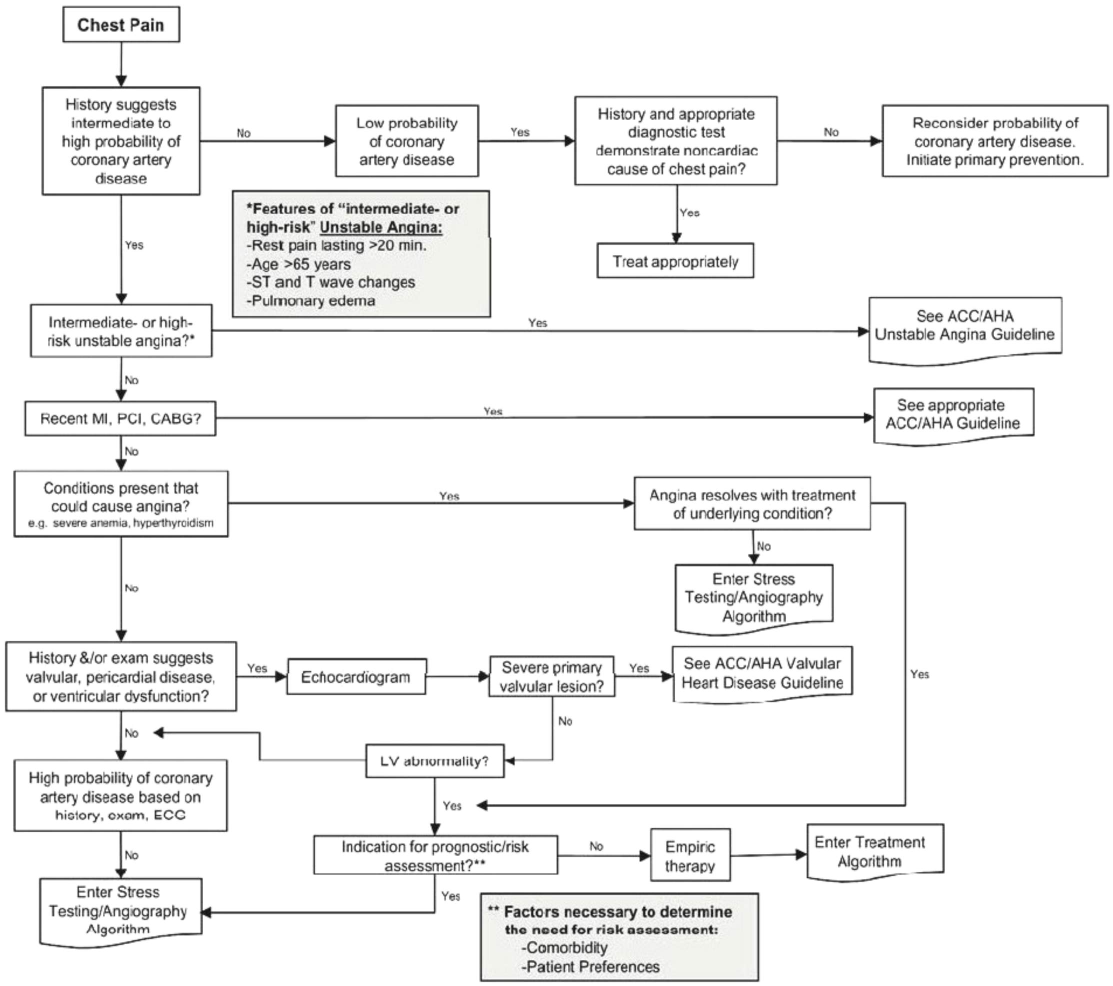


Figure 2.2 An example of Clinical assessment for Chest Pain (American College of Cardiology Foundation and the American Heart Association) [3]

informatics [20,21]. An unstructured clinical narrative format leads itself to misinterpretation of knowledge and unclear decision processes. As an approach to overcome the problem, many guidelines include diagram to describe clinical logics in addition to the narrative statement within guidelines. Figure 2.2 shows an example of clinical assessment logic in a published guideline for chest pain [3]. Having a standard way to describe logics and link to resources is an issue in health care informatics [4,12].

Among several attempts to standardize clinical communication, medical logic modules (MLMs) [22] were developed to describe clinical decision logics for diseases. They are written in Arden Syntax [23,24], which was developed as a standard modular representation of medical knowledge and is now a part of HL7 standard [6]. The first version of the Arden Syntax was administered and issued by the American Society for Testing and Materials (ASTM). Since 1998, the Arden Syntax group is part of the HL7 [6] organization, which administrates many widely accepted standards in health care informatics. The goal of the MLM is primarily to store constructive knowledge as a form of logics to evoke alerts and reminders to medical practitioners. The scope of the Arden Syntax is mostly limited to MLMs and each module represents a small clinical knowledge for a single decision making. For example, contraindication alerts, management suggestions, data interpretations, treatment protocols, and diagnosis scores are examples of the knowledge that can be represented using MLMs. MLM can also include management information to help maintain a knowledge base of MLMs and link to other supportive resources of knowledge. Health care personnel can create MLMs using Arden Syntax, and the MLMs can be used directly by many health information systems supporting Arden Syntax [25]. Many commercial vendors adopted the standard and included it in their products [26-28].

2.3 CPG implementation

GLIF (Guideline Interchange Format) [4,12,29], is an abstract model for representing CPG, as developed by InterMed Project [30], to enable CPG sharing among different local clinical settings through standardized translation interfaces [31]. Closely analyzing previously developed CPG formats and guidelines in the formats, such as GEODE-CM [32], MBTA [33], EON [34], GLIF defined the essential and common components of CPG to develop a system-neutral model of medical knowledge represented in the various CPG formats. Guiding concepts for GLIF incorporated computer-based execution at three levels: conceptual flowchart, computer specification, and implementation specification. Tools were developed to support each level, such as editing and validation. The concept validity was demonstrated in one experimental system that showed how implementation would work. The tools showed the soundness of the model and its applicability to various aspects of clinical information systems. Those are mostly concerned with how to encode guidelines in a formal language to illustrate structural information integrating patient records and how to make guidelines that can be incorporated more constructively. It thus promotes improved clinical decision making by humans by providing a more consistent implementation of CPG, but it does not provide a better tool for direct use by clinicians from editing CPG through planning and management of patient care process based on CPG. In this research, no unified system approach is provided encompassing the entire care process. Users still have difficulty in understanding many logics and relationship between those in large scale and figuring out decision history for a particular patient case.

A key challenge to implementing CPG is to provide a tool that enables users to intuitively and appropriately interpret clinical knowledge. Recognizing the critical aspects of clinical data and the associated decision logic can easily become fairly complex as patient care proceeds. In many cases, more than one guideline is usually involved and every decision is registered to information system along the patient care process. This leads to difficulty in managing knowledge and patient information increasing detail level from contextual view to small features in a comprehensive way. One approach to this issue is the use of a navigation tool that guides clinicians through the care process guidelines and actual patient treatment process that results. Navigation facilitates the situation awareness for the clinicians by:

- clarifying relationship on how individual tasks are related, e.g. what and why a certain task is succeeded,
- clarifying what or how decisions are made and what alternative care process options are available,
- recognizing why and how much a decision has advantage(s) against other alternatives,
- if the past decision is related to the current decision, recognizing the nature of that relationship and discerning how the past decision affects the current decision
- if a medical process in progress is suboptimal, finding which previous decision step is the clinical branch point to return to in making a revised decision

Navigation information and its associated design have been facilitated by visualizing as a roadmap of patient care process. Visualization and graph drawing community have provided tools clearly representing the data-driven topologic information to aid navigation through the data. The following sections discussed how visualization researchers have approached to visually represent information and optimally combine the visualization with interaction paradigms to help discover knowledge for different domain problems.

2.4 Scientific/Information Visualization

In early age of visualization, researchers tried to help scientists gain the insight of large amount of scientific simulation data with images visualized upon the data [35,36]. The process includes data acquisition, data transformation, visual transformation of the data, and rendering the data in computer image. The dimensions and quantities in scientific data are clearly and well defined. The visualization was static image general tool results rather than exploration tool for finding desired resultant outcome, since the computing power did not allow users to interactively transform data and visuals. In most cases, until achieving the satisfactory resultant image, it takes several trials with different parameters for data calculation, data transformation, or visualization setting. Researchers in both scientific and information visualization started to realize good interaction design is crucial for involving more human expertise in information exploration process as well as making refined visualization. One of the essentials in the visualization and interaction design is that it should not ignore the real world process and conventional understanding of the required tasks [13,14,37]. For example, information visualization has tried to support the current data mining tasks and enhance them with visuals, instead of providing completely new automation from the data handling to final decision making [38,39]. Visual queries and visualization supporting data cube concept are good examples of combining common data retrieval and visualization of the data, remaining user tasks in simple way in spite of the complex database schema behind the user interaction [40]. Instead of the approaches interleaving data mining tasks and visualization, data mining algorithms and visualizations are seamlessly coordinated and embedded into a procedure so that broader range of tasks for knowledge discovery process remain in a unified abstract [39,41].

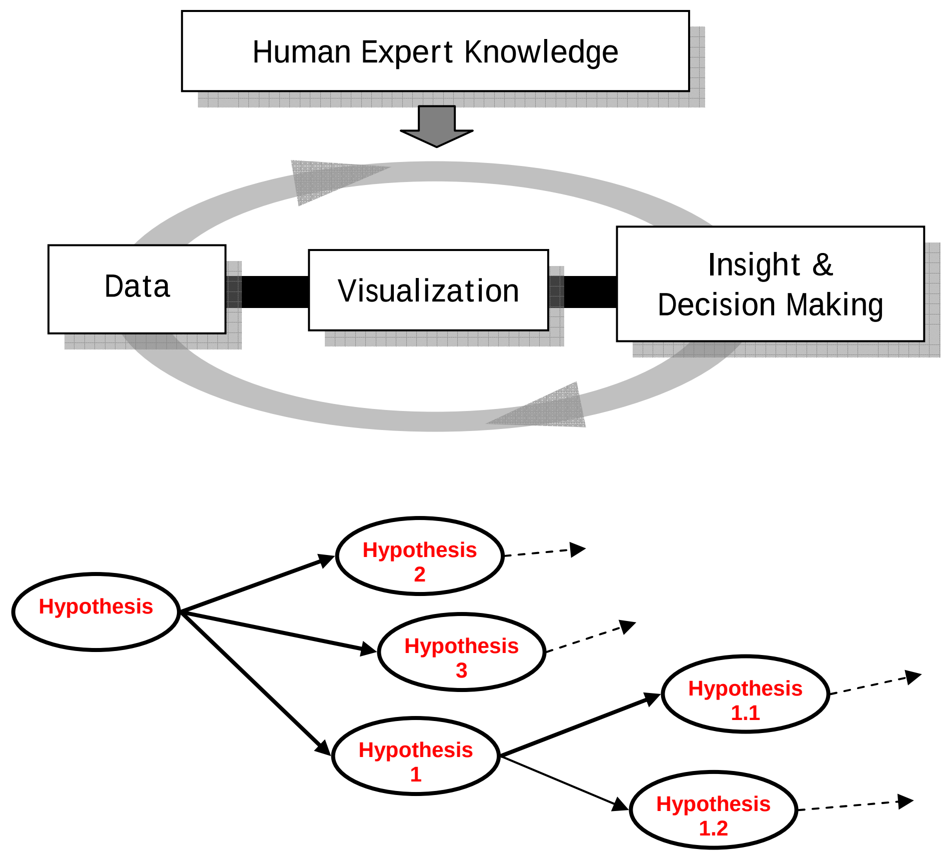


Figure 2.3 Illustration of visual data exploration tasks and how hypothesis-evaluation process advances toward a conclusive result

2.5 Visual Knowledge Discovery

The user-centered information exploration and knowledge discovery disciplines are based on "hypothesis-evaluation process". Process toward the decision making in visual data exploration requires several iterations of hypothesis-evaluation processes of "*What-*

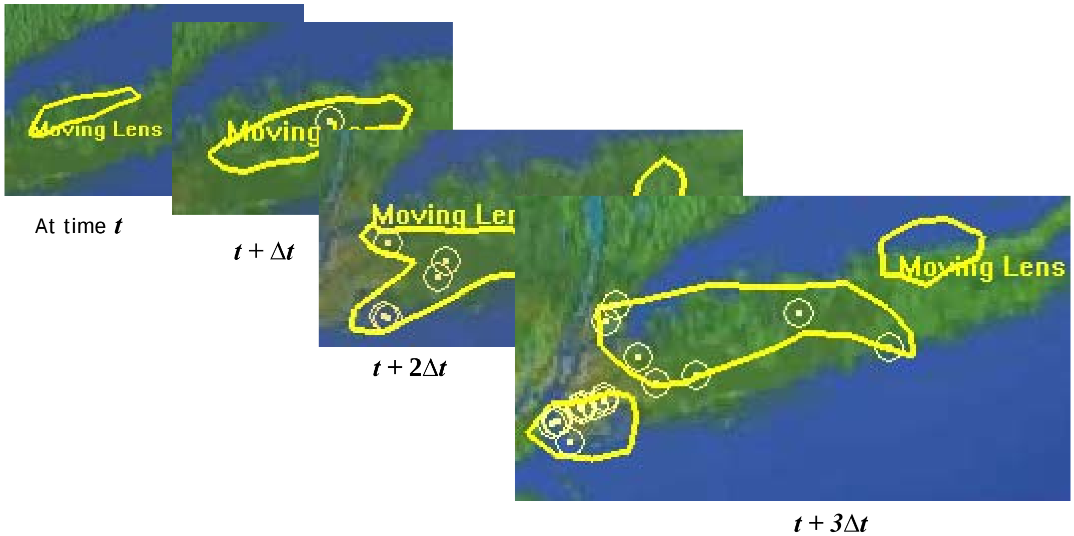
if' based analysis, as illustrated in Figure 2.3. This process is quite similar to clinical decision making through diagnostic hypothesis and clinical test evaluating the hypothesis. In order to achieve knowledge through the tasks, user interaction as well as representation should be carefully coordinated so that the knowledge discovery paths appropriately guide decision making. Sense making model [42] discussed general idea about steps of tasks about how users effectively reach a decision. This user-centered interaction design must incorporate subject matter experts knowledge into the visual interactivity envisioned [43,44].

Information exploration or data analysis process rarely starts with prior knowledge about the dataset or clear understanding of dataset. Even problems have not been able to be identified until analysts begin information exploration, because of insufficient insight about dataset, which is in huge size, in large dimension, and disparate. Datasets are basically presented texturally and thus amount of data displayed to users are quite limited. Visual data exploration enables human to be involved in the data exploration process and combine general knowledge with large storage space and computing power available in computer systems these days. As illustrated in the Figure 2.3, through the iterative visual exploration process involving human expertise, users are moving forward creating and evaluating analysis hypothesis toward conclusive knowledge discovery.

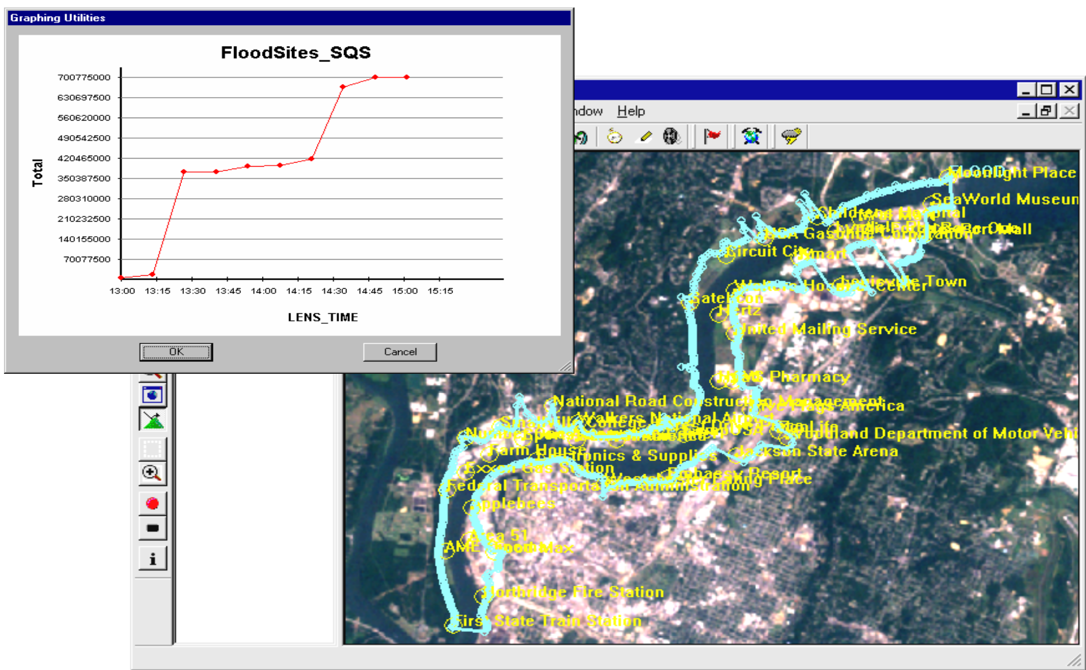
The basic idea is to present data in visual form, allowing users to get insight into the data, intuitively interact with data, and draw conclusions in understandable form. These visual approaches enable the expected tasks to be performed in a unified abstract from simple data retrieval through a final decision making. It thus alleviates the problem that running automation of the process does seldom convince decision makers. Based upon the visual understanding, results through expert validation enable to build efficient and sound knowledge.

A research work, as referred to *information foraging theory* [45], analyzed the process of gathering information from creating hypotheses to gaining knowledge, for optimal design of information system. The research studied the optimal foraging theory within biology for understanding the opportunities and forces of adaptation, and claimed that the theory can help understand existing human adaptations for gaining and making sense out of information. Peter *et al.* also analyzed the human information foraging behavior and applied it to information visualization system to achieve better guiding path toward conclusion [46,47]. The theory can help particularly for design of the human-centered visual data exploration system, which needs design philosophy guiding toward a certain desired and clear direction. Visual data exploration systems provide flexible and comprehensive tools for analysis without heavy dependence on preconceived assumptions.

For example, EDA (Explorative Data Analysis) uses a sequence of data exploration techniques while seeing intermediate results and then decide the following tasks, as opposed to a batch process of all those. The optimal information foraging could also be achieved by use of a single visual metaphor for EDA tasks. Lee *et al.* [7,8] proposed a geospatial information exploration tool that uses lens metaphor for various data analysis functions. Using the lens interface (See Figure 2.4), a visual metaphor for defining a certain area on the map, users can do various exploratory data analysis tasks for the defined area. The lens area can be manually defined by user, geographic information, or simulation data. The basic tools with lens interface include statistical data visualization



(a)



(b)

Figure 2.4 Geospatial information exploration with lens visualization [7,8] (a) Spatio-temporal visualization by data filtering lens paradigm (b) Statistical analysis by use of lens. Lens area is defined by flood simulation over time and the monetary value of increased damage in the lens area is automatically queried from a database. The graph in the linked view shows the pattern of damage with respect to time.

within the lens area in a view linked to lens interface, chained visualization showing data dependency behavior between several lens areas, and spatio-temporal visualization with running clock. The individual tool or mixed use of more than one tool is all based on the lens paradigm. The user tasks, resultant visualization, and retrieved data are also recorded based on the entity of lens interface. The unified interface paradigm enables analysts to think of, represent, and navigate a sequence of tasks only with the concept of lens. However, thinking and managing the relationship between several different and somehow related tasks were completely up to users. There is not any supporting tool in the system for users to link them to make sense of the performed tasks.

The problem arisen in using the EDA tools is that users can hardly manage the sequence of tasks, involved logics, decisions, and intermediate results, even though the unified interface approach helps describe them better. Enhancing the management of tasks does give not only a better tool to describe the analysis process, but also a tool helping others navigate the analysis space comprised with tasks, logics, and resources. Providing an established framework of process makes performing similar analysis or related analysis in the future much easier.

2.6 Graph Visualization and Visual Knowledge Representation

Early studies in graph drawing tried to represent a fixed map of complex relationship information found in high dimensional data [48]. Graph visualization addresses the problems of drawing large scale structural information within a limited screen space. By optimally placing visuals on the screen and adjusting the visual properties of them, it

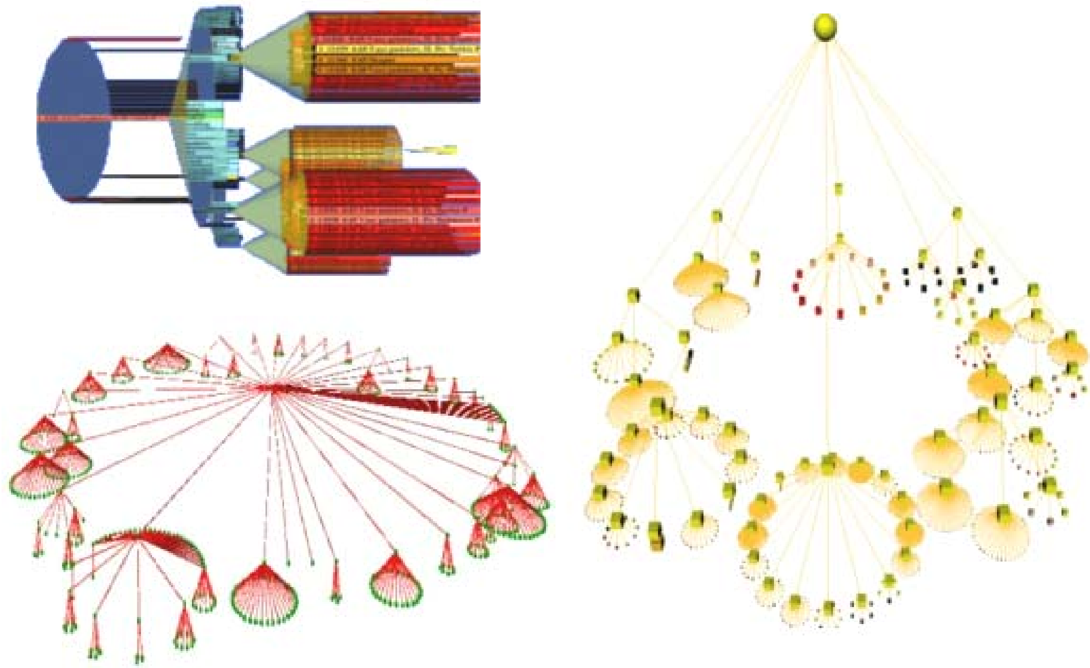
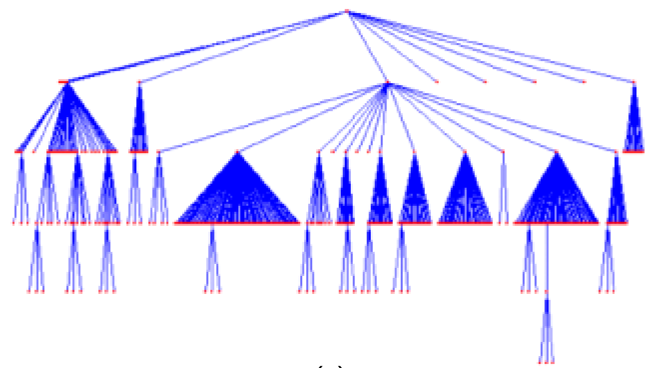
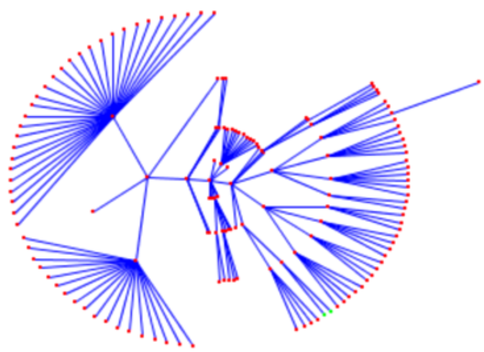


Figure 2.5 3D hierarchy visualization examples [2]

provides better understandable drawings. Large graph is not the only challenge for graph visualization. If large structure is successfully drawn, however, by giving visual information overload to users, usability and view-ability become issues since users can hardly discern graph elements, nodes and edges. Herman *et al.* [2] discussed various criteria for graph visualization application and discussed navigation based on graph visualization. Considering the graph visualization as an information visualization, various issues have been discussed. 3D graph visualization ensures more space to draw the structural information, but it gives user perception and interaction challenge, since the front graph



(a)



(b)

Figure 2.6 (a) Reingold and Tilford tree visualization algorithm and (b) radial layout of tree information [2]

elements obscure graph elements beyond them in the visual cue. In Figure 2.5, large part of the graph is hidden by other visual objects in the current projection. For this reason, excellence in viewing control is required for exploration of structural information by navigation in 3D space.

Tree is a reduced form of a graph in terms of its complexity. Classic tree layout, Reingold and Tilford algorithm [49] (See Figure 2.6 (a)) meets the aesthetic rules, such as isomorphic substructure, straight lines, evenly distributed nodes and edges, and same

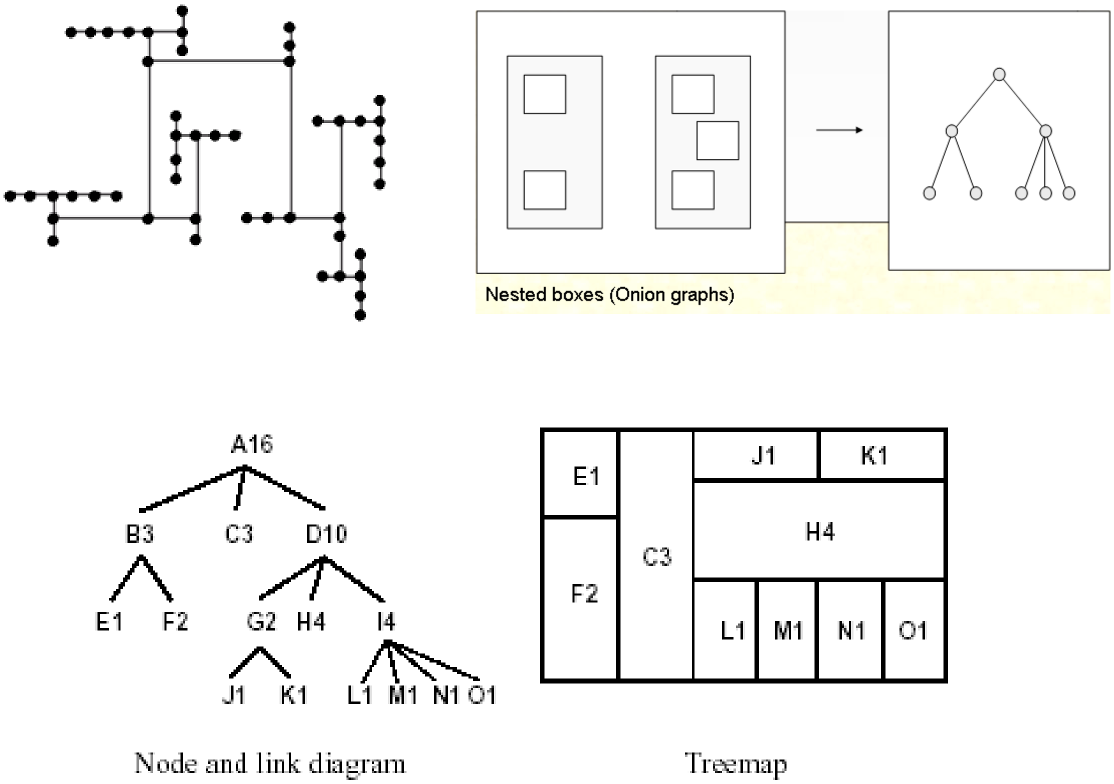


Figure.2.7 Examples of various tree visualizations : Top left shows H-tree layout. Top right shows nested graph of hierarchical information. Bottom shows hierarchical information with Treemap algorithm [2].

length of edges. The classic tree layout reflects well the intrinsic hierarchy of the data that children nodes are “below” under the common ancestor node. In contrast, radial tree layout [50] (shown in Figure 2.6(b)) and H-tree layout for binary tree [51] (in the top-left of Figure 2.7) represent the root less clearly. The layouts are useful particularly for the tree applications where the hierarchical meaning should not be necessarily dominant. Tree-Maps [52] convey scalar information on each node encoded with rectangular size compromising its poor ability to percept structure in this representation. Onion-graphs [53] represent tree with sequence of nested boxes (See Figure 2.7).

Navigation design is largely dependent upon the type of graph layout and application. Zooming and panning are typical user operations expected in most visualizations as well as graph visualizations. For geometric zooming in the graph visualization, the technique is quite simply done by adjusting screen transformations. Any further pixel-level operation such as anti-aliasing is not necessary. However, the semantic zooming into information contents of tree components should be appropriately shown. Determining the rendering of the semantics requires additional design philosophy and computation. Panning is frequently combined both with and without zooming operation to usually center a portion of visualization. Visualization contents may be out of screen boundary by those operations and cannot appear until a user controls zooming or panning. To avoid the situation that critical visuals are hidden, Focus+Context techniques have been introduced. This will be discussed in detail in a following chapter.

By the fact that knowledge is frequently described with process, graph and navigation onto roadmap description with graph visualization can be used for description of knowledge or knowledge discovery process. The graph components could be description of necessary tasks and resources for “process”. For example, the node components represent action and edge components illustrate the transition between the action nodes. The roadmap description with graph visualization and navigation is then used as a tool as well as just pictorial representation. This could be also a note taking tool that helps experts easily externalize the concept of potential tasks and actions, relationship between them, rules between them, or workflow.

Visual programming paradigms found in some of the analytic visualization [54,55] systems provide editing tools that allow users to constructively compose a sequence of modular tasks. The tasks are described with corresponding visuals that permit exploration of task details such as intermediate results [56-58]. In most applications, the depth of the tasks is not that deep, the tasks are well-defined, decisions at each task are relatively straightforward, the linkage between tasks is simpler, and the number of tasks to be managed is finite. None of these conditions apply to CPG representation.

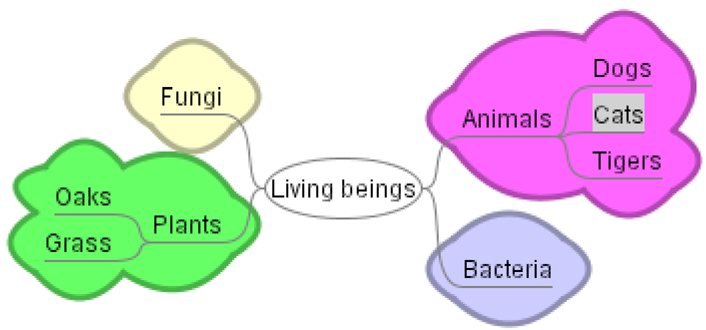


Figure 2.8 An implementation of mind map (Free mind [1])

More sophisticated attempts to visualize the decision making process have incorporated psychological concepts. One system approach (Mindmap [59]) represents knowledge as a radially-connected series of nodes of related information placing a problem of issue on the center of image. The lines between the nodes do not reflect structured relationships (See Figure 2.8) [1]. It is a method about how to note "somewhat related" pieces of discrete components. It can be a flexible note taking tool, but, as the structure becomes more complex, the lack of relationship definition leads to inconsistency in interpretation.

Researchers in information visualization and visual analytics have improved visualizations and incorporated user interaction into the models to facilitate the knowledge discovery process [13,14,44]. This means building not only a better visualization system but also a system with sound model for task-oriented knowledge discovery and seamless transition between the discovery tasks. Instead of using separate tools, each of which is optimized for a local task, a system with unified concept encompassing from creating an analysis hypothesis to providing a visual presentation of founding has been discussed [44]. Not only large disparate datasets but also heterogeneous tasks make it difficult to have such a system. Multidisciplinary works need to be done, for example, research on how best to describe and communicate the domain specific knowledge, in-depth survey of the domain expert behavior for knowledge discovery, better human-computer interaction techniques, and systems engineering for interfacing existing systems well.

CPG based information system should not be much different from the design philosophy discussed above. Expected usage of CPG includes the both aspects of rigorous use of well-defined knowledge and exploratory knowledge discovery. For relatively well defined and frequently faced clinical cases, clinical practice on different occasions may not be dissimilar to each other. In contrast, for a rarely encountered and quite complicated case, clinician needs to carefully look into patient-specifics not shown in guidelines, previous patient cases, and possibly create a new care process plan. Exploratory tasks in this domain are for not only planning a new patient care process but also exploration of new relationship between previous actions, decision, and electronic records. It is much more for relationship finding, similar to those with knowledge discovery in database, based on available data and knowledge. For example, referring to patient history is not simply finding a data item but drawing a relationship between the patient status and information around previous decisions.

In the medical area, Protégé [60,61], a computer-based ontology authoring tool, has been used as a tool that allows users to visually author GLIF and evaluate the resultant structure. Protégé is a tool developed to represent a general knowledge structure and evaluate the structure. InterMed project [30] adapted the tool to visually represent CPG structure and demonstrated its capabilities. This is more like a drawing tool specialized in composition of GLIF primitives, because it is focused mainly on authoring and is not designed to integrate actual data (patient records). Another project, KNAVE-II [62,63], shows a temporal based care process description ideal for arranging care process along a time line. Alarming and reminder of clinical action is a highly required feature in guideline based clinical information system. Timeline based analysis enables users to see how a task has been processed in timely manner. It gives easy way of identifying time-critical tasks and planning tasks arranged , but it does not incorporate strong capability about possibly large and complex decision making logics in contextual view of patient care process. Neither work in the above successfully supports the clinical knowledge representation and application of the knowledge in the patient care process. Especially, none of them supports large enough guideline structure and decision oriented tasks.

CHAPTER 3 CPG VISUALIZATION CRITERIA AND DESIGN

The ultimate aim of CPG, regardless of its type used, is to clearly describe care process with decision logic, diagnostic and treatment tasks, and patient status. From the point of view in developing a visual CPG tool, the essential case-invariant components have to be delineated, along with a representational approach. In the InterMed approach to GLIF [30], components consist of *action steps*, *conditional steps*, *branch steps*, and *synchronization steps*. However, dialogue-based stepwise CPG implementations found in currently available systems neither show how the components are interconnected in a contextual view nor allow doctors to make decision with extensive view of prospective care processes in mind. Moreover, in the common clinical situation with multiple interrelated symptoms, the guideline becomes difficult to describe clearly, with complex underlying logical conceptual frame work. The functional requirements for any CPG visualization derive from these current limitations and include:

- representing complex and ever-changing patient care process efficiently (Visualization, Refinement, and Dissemination of knowledge)

- providing visualization and interaction design that enables users to straightforwardly edit and explore both context and details (Intuitive and comprehensive authoring and navigation)
- seamless transition from knowledge to its actual practice and representation (Versatility in knowledge and its production representation)
- intuitive tool analyzing various patient cases to describe a new guideline
- integrating different levels of importance of each data point or decision in the CPG representation as a factor of knowledge or practice assessment (Decision Support)

How these criteria are followed to develop a novel visualization of CPG is discussed in the next few sections.

3.1 Dynamic Hierarchy

The components model for the visualization uses the well-established format of the GLIF specification to support and take advantage of further developed and refined MLMs. The design also considers how the visualization can handle the various scenarios, such as multiple symptoms situation. This section discusses how dynamic hierarchy design can address such issues. Key issue is making the complex structure perceptually simpler by analyzing user demand and behavior expected in essential CPG structure navigation. For example, composition of multiple structures, expansion of compressed structures, and display of semantic information of nodes increase the visual complexity.

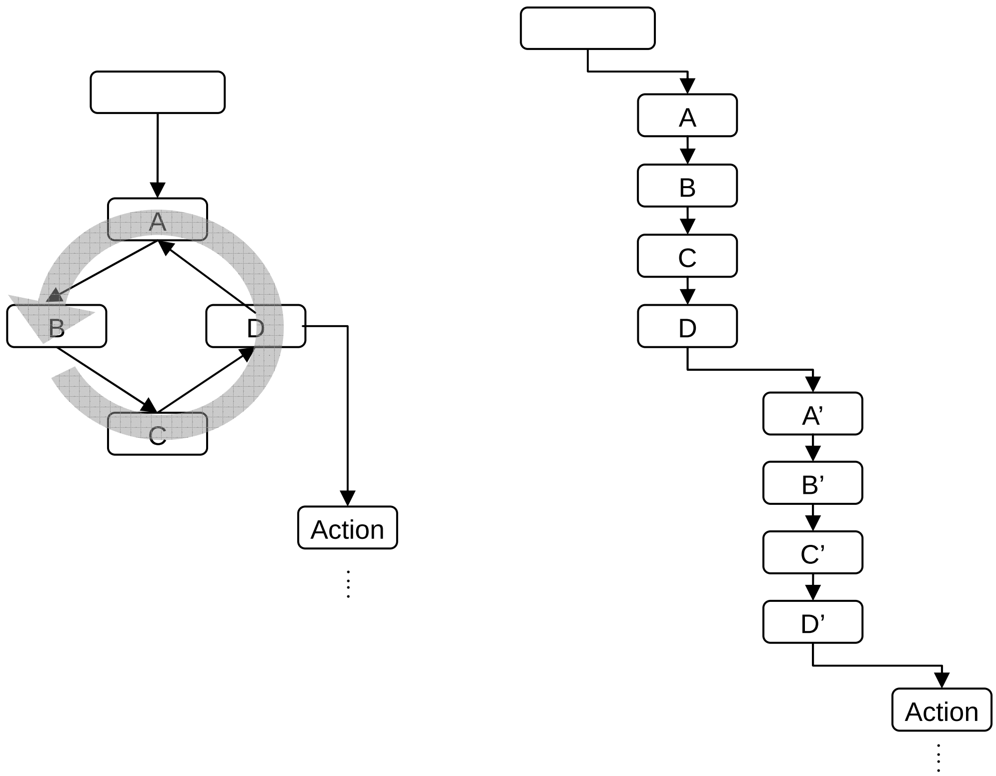


Figure 3.1 Expansion of cyclic graph description of repeated tasks into linearly extended structure: Left graph shows a cyclic graph with node A, B, C, and D. Right graph unfolds the two repetition of the cyclic graph in the left graph.

In CPG visualization, things to be illustrated are basically routes of clinical workflow. How well a user goes through the each task in a CPG depends much on the degree of understanding the visual representation of the CPG. Difficulty in recognition due to the visual complexity or unclear visual description may cause unexpected navigation action, which might vary depending on the user. Achieving visual simplicity does not always guarantee clear understanding especially when it is considered with navigation. Compromising simplicity in visuals often remarkably improves user navigation design.

In many CPGs, iterative sequence of tasks is expressed with cyclic graph as seen in the left graph of Figure 3.1. For example, repeatedly taking some medicine and treatment until something desirable happens is a simple description of this case. With the cyclic graph, difference in one cycle from the previous cycle is hardly captured. Cyclic graph for iterative process might be fine in representation of only CPG not patient care process, because it easily leads to both the vagueness in navigation and the limitation in representation. In the proposed visualization here, the cycles are unfolded into a set of connected linear graphs increasing the structure size (See Figure 3.1).

It is essential to avoid over-specification that can occur if every module in the

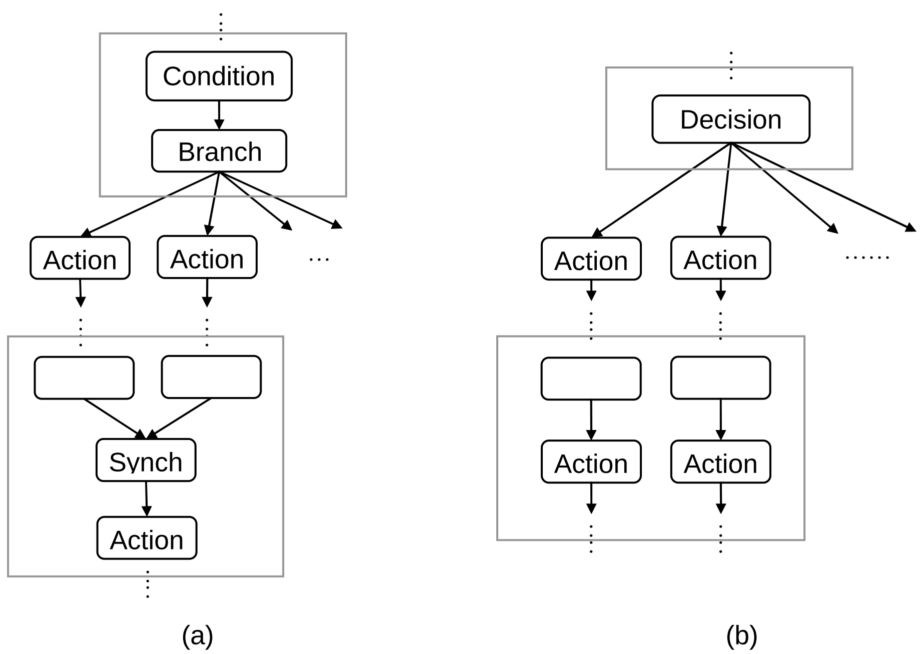


Figure 3.2 Node and hierarchy redesign: (a) Illustration of an example of *conditional*, *branch*, *action* and *synchronization* (Synch in the above diagram) steps used in GLIF [4] (b) Introduction of *decision* node by combining conditional and branch nodes and removal of synchronization node for better illustration of branched care process in the streamlined sense

specification is encoded to a separate correspondent visual, since this can result in visual clutter. As seen in the example diagram in Figure 3.2(a), the specification in the model consists of a set of four steps in care process that are linked together in a directed graph [4,29]. Among the four steps, conditional steps, branch steps, and synchronization steps can be reformed for clearer visual representation. Because a conditional step is always followed by a branch step, they are redundant for visual use, although the two steps need to be distinguished for other purposes such as describing functional modules in implementation. The two steps can be combined into a single decision step so that action steps are directly branched from decision steps as shown in Figure3.2 (b). Synchronization step illustrates that more than one process conjoin to a step beginning the next procedure that is executed after antecedent procedures arisen from separate decision tree (bottom Figure3.2 (a)). The notation is simple and may be helpful in highlighting the nonlinear characteristics of CPG. The apparent linear clinical process that is observed in retrospective analysis can be misleading, as it is the end product of a branched decision tree that has already been pruned by the actual clinical process. The visualization model proposed maintains the logical relationships to avoid ambiguity in the event of a reassessment of clinical case driven by a suboptimal outcome. This is particularly important for those guidelines that may involve recursive elements.

When decisions are being made along patient care process, suboptimal care options are discarded by taking the best care option. However, the discarded suboptimal care options are critically important especially for reviewing purpose or communication of decision makings. A decision is represented better with suboptimal care options as well as chosen one. This tells that several options have been considered and, after considering all of them, one has been chosen among the options. Since each of the options has substructures of many decision logics and tasks, representing all of the options involves showing not only a task very next to the current decision but also possibly many sets of large structure of tasks.

Such navigation oriented structural representation easily increases the size of the structure. Dynamical hierarchy representation is essential in order to resolve the problem of navigating large structure. While Protégé, an ontology editing tool, and other guideline implementations mostly concern guidelines for single condition [31,60,64], the visualization system proposed in this dissertation provides patient-centric view involving multiple symptoms-guidelines. This involves recursive representation of multiple guidelines, repetitive occurrence of a care process, and chained guidelines. This is required to address the issue of how to represent an incremental structure which is being created as patient care proceeds.

The visualization should represent a structure in a uniform manner whether it is highly complex or not. This issue is referred to as predictability in graph drawing, by which is meant that repeated runs of a graph layout algorithm for similar graphs do not produce drastically different graphs [2]. This is critical characteristic especially for the case when a graph needs to be incrementally or interactively shown. While a clinician is authoring a clinical practice guideline, addition or removal of a graph component should preserve his or her mental map visually. This is also an important requirement in collaborative planning of a patient care process, as it fosters consistent understanding among the participants.

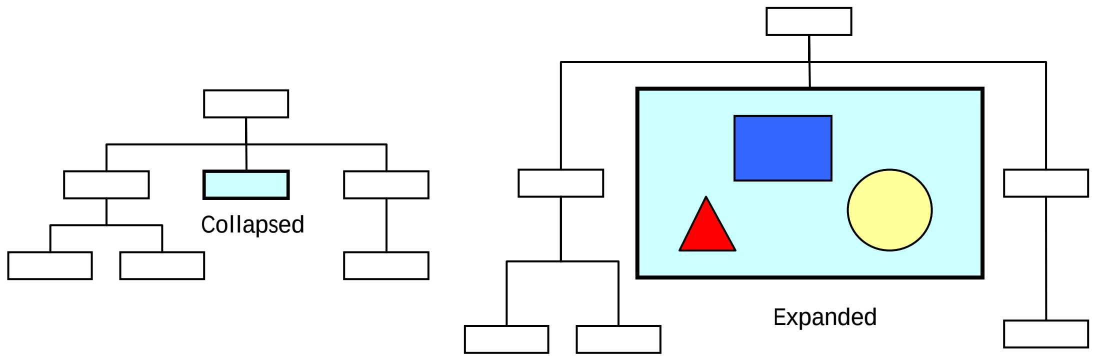


Figure 3.3 Nested interface example within hierarchy drawing

3.2 Context and Detail

Context and details should be visualized in concert, since it is necessary for clinicians to take care the patient based on both contextual understanding and care process detail. Given the logical structure of a clinical problem, a form of structured CPG, a doctor should be able to navigate the logical structure comprising the CPG to construct a mental map of the care process. Two aspects of details are concerned here. The one is about structural information details that are decision logics and order of clinical actions. When the attention is called on a task, the previous and following decisions and tasks are of main interest. The other aspect of details is semantic information detail of a particular clinical action. When the CPG is applied to actual patient care process, Electronic Medical Record (EMR) information and annotation of a task illustrate evidences for the patient-specific care and associated decision makings. The evidences build up the idea about how decisions are made, how each of the tasks is done, and what the current status is for a particular patient. To accommodate the semantic details, the design adapts nested user interface components [65] (See Figure 3.3). The hypermedia data types of EMR (textural data, image, drawing, sound, video, graph, etc) are integrated into the nested interface components associated with the node. This EMR tightly integrated into patient care context are retrieved later by users having idea about what decision results in the EMR and how the EMR affects the further decision. Despite the various types, they should be handled by a single abstract user interaction. Interactions incorporated with the information should be performed in a simple way.

Through the addition of patient details, the clinician can navigate the CPG structure while more closely examining action steps, recalling or recognizing the history and logics involved in the decisions made before. The context achieved by navigation is improved by the addition of patient specific details to help doctors apply the knowledge specific to the patient efficiently and make further decisions properly. As decisions are being made, the patient status and care process are updated. The additional complexity from this ever-changing patient care process and patient status makes it difficult for medical practitioners to maintain an accurate overview of the care process. The visualization model is specifically designed to support the contextual understanding and details despite the complexities.

3.3 Significance Encoding

In addition to aiding the development of CPG, a visualization model allows for review of the influence of each decision on the overall care process. As each decision is being made, decision analysis is used to evaluate each alternative and develop a rank list of the preferred alternatives. The ranking information should be conveyed in the visualization. The rank is easily recognized for a few alternatives, but the large number of decisions involved in the entire patient care process makes it difficult to recall how the decisions have been made. Decision scores used for the decision analysis are also care process specific, so visualizing the information differentiates view of care process originated from a guideline structure.

Emphasis on the critical action steps should be conveyed in the visualization so that practitioners can readily discern the significance of each action among the many others in the visualization. Having such significance information presented visually further facilitates coordination of care between the various involved clinicians by highlighting the critical issues in the patient care. This encodes opinion based on expert knowledge of each individual.

CHAPTER 4 *FOCUS* + *CONTEXT* TREE VISUALIZATION

Incorporating the need for presenting a large dynamic hierarchy and the requirement for maintaining overall context while focusing on a specific detail (the Focus+Context paradigm [13,14,66]), drives the underlying graphical design specifications. Focus+Context paradigm has been introduced to synthesize informative graphics not only for graph visualization. A typical example of addressing this problem is fisheye distortion [9]. (See Figure 4.1)

In limited viewable dimension, a fixed global scale makes it difficult to depict both details and overview. For example, understanding long driving direction requires several maps with varying scale, a brief map to have overall understanding of direction and distance, and detail maps to understand local roadmap. Like the road map example, visualization users expect contextual understanding, mostly relationship finding, with global view and exploration of local detail with focused detail view. It is often difficult to gain the two in a view, so special care needs to be taken in the design.

To make visualization informative, not only varying physical magnification but also changing levels of semantic details need to be essentially involved. To address this issue, visualization design provides how to combine the various scales and semantic details in a seamless way. It is also necessary to research how users control and perceive the detail and contextual visuals.

A design that makes users focus on intended portion of visualization while they are maintaining context is a good example guiding users through a proper path. Especially in graph visualization, properly combining a focused substructure details with a global context view is main issue. The graph visualization is usually used as a tool for exploration of structural information.

CPG structure visualization should strictly avoid hiding any part of the structure out of view, since anything in the clinical care context can be critical and thus nothing should be completely overlooked. This can be achieved by using hyperbolic tree visualization [17] which utilizes hyperbolic geometry to draw large hierarchical structures in a limited space. The visualization is controlled by an algorithm that responds

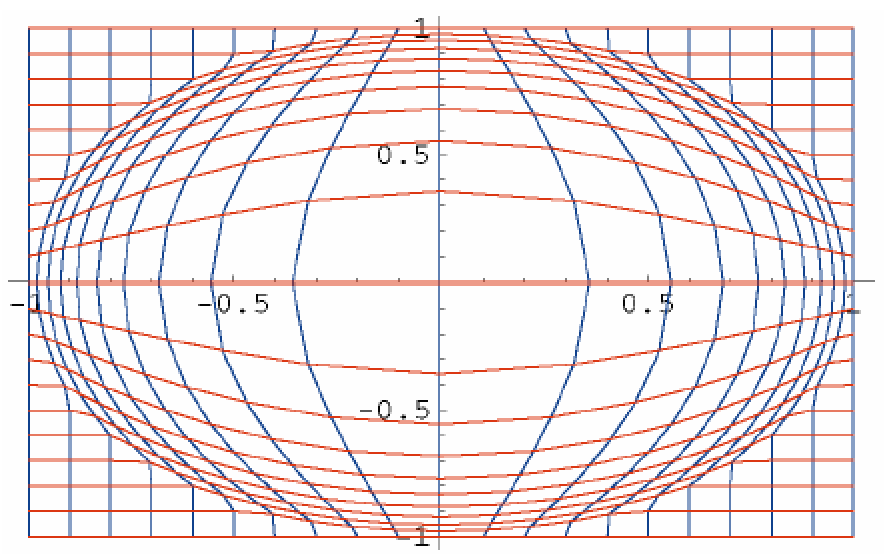


Figure 4.1 Fisheye distortion of a regular grid of the plane [2,9]

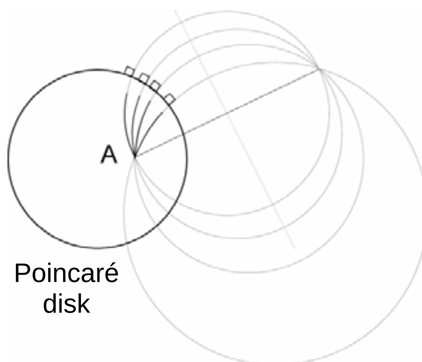
to the users' initiation of focusing onto a specific portion of the structure.

4.1 Fisheye view

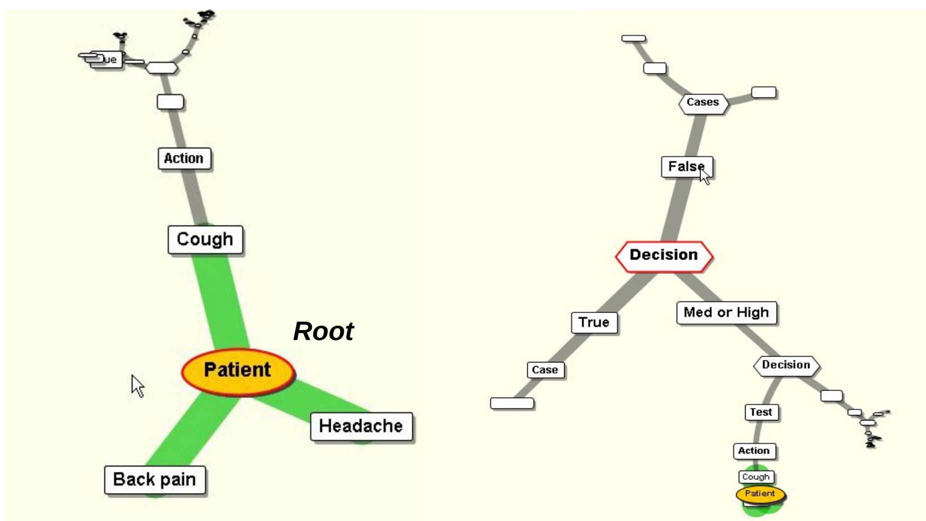
Graphical fisheye views are popular techniques for Focus+Context. Fisheye views imitate the well-known fisheye lens effect by enlarging an area of interest and showing other portions of the image with successively less detail. A fisheye view of graph is drawn by mapping visuals in a regular grid to a distortion map described in Figure 4.1. The fisheye technique is independent of the layout algorithm and is defined as a separate processing step on the graphical layout of the graph. This independence has positive and negative aspects. On the positive side, it allows for a modular organization of software in which fisheye is a separate step in the graph rendering pipeline somewhere between the layout module and the actual display. Fisheye can also be significantly faster than the layout algorithm, which is an important issue for interaction. Complexity in algorithms is invariant no matter how complex the contents in the graph are. However, the fisheye distortion may destroy the aesthetics governing the layout algorithm. For example, it can cause unwanted graph components merging. The hyperbolic layout is special because it is a graph layout algorithm that was developed with the Focus+Context distortion in mind and resembles of fisheye distortion conserving the tree structure information.

4.2 Hyperbolic Tree

The *Focus+Context* capability is inherently provided in the hyperbolic tree visualization based on the *Poincaré* disk model [17,67]. The parallel posture exception in hyperbolic geometry alleviates the problem associated with the difficulty in drawing



(a)



(b)

Figure 4.2 Hyperbolic geometry with *Poincaré* disk model: (a) Geodesics used for edges stretched from a point A on Poincaré disk. (b) Two different layouts out of same hierarchy are shown in a hyperbolic geometry model, *Poincaré* disk. The layout shown in the left focuses patient node and draws structure father from the patient node smaller in size. The layout shown in the right focuses a decision node under the 'Cough' symptom node.

many lines from a point [2,17]. A geodesic that crosses at a given point (in (a) of the Figure 4.2) inside the disk must lie on the circle perpendicular to the disk circumference. There could be infinite number of geodesics, a locally length-minimizing curve, that are parallel to each other in this hyperbolic geometry. For any given point in *Poincaré* disk, we can define a node at any point and edges stretched from the node to its children nodes. It guarantees that edges to children nodes never cross each other, otherwise it results in poor readability of the hierarchy.

Angles between the adjacent edges and length of each edge determine the overall dimensions of the parent-children structure. The geodesic length is determined by a continuous function defined over the *Poincaré* disk that gives longer length for the edge closer to the center and shorter for the edge near boundary. The angle between the adjacent sibling nodes is recursively calculated with weight for each node in the way that it assigns more weight for the node with more children. Consequently, unless the hierarchy is changed, wherever the node is in the disk, the algorithm ensures wider angles for nodes with heavy weight. Every time the hierarchy is changed or a root position is changed, the algorithm updates the position of the all the node from the root to leaves by recursively calculating every angle and the length. Defining a node position in the hyperbolic geometry and transformation between hyperbolic geometry and screen coordinate are explained in Appendix I.

As seen in the Figure 4.3, the center area in the windows takes more space than the area near the windows boundary. Hyperbolic geometry places large number of nodes as evenly as possible and the nonlinear function decreasing the edge length from the center to the circumference allows an exponentially growing number of nodes in tree structure.

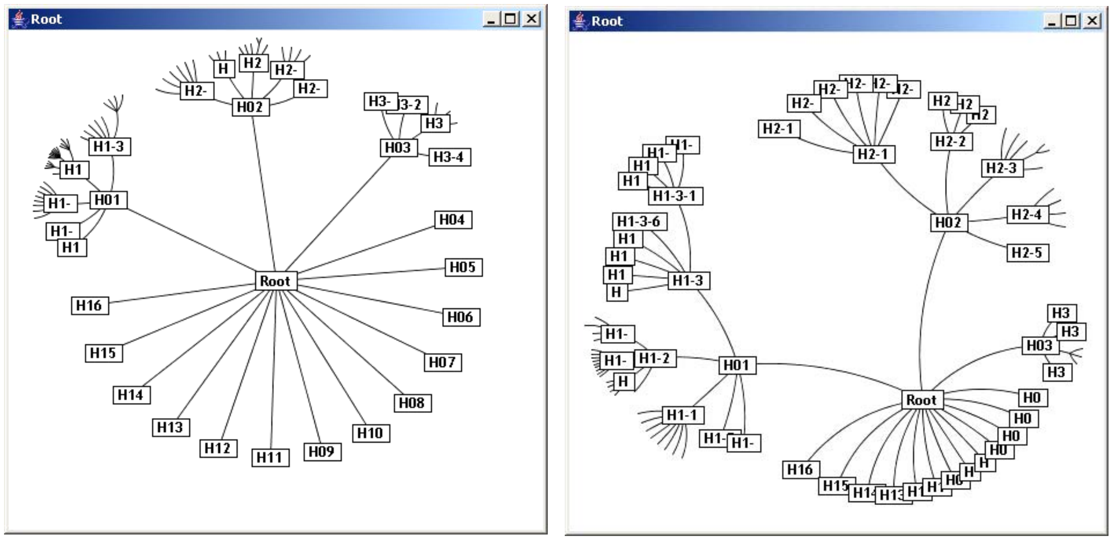


Figure 4.3 Hyperbolic tree layout examples

If a user wants to see a node with the more focused view than other nodes, the user drags the node into the center area and then sees the tree with a view focused to the node. Figure 4.4 shows the tree implementation fit to the different aspect ratio producing different perceptional view by user control. In the user perception point of view, it does not have absolute indication of the "*root*" node, while some tree layouts, such as Reingold and Tilford algorithm mentioned in Chapter 2, do. Any node can be located in the center of the view and it is on the focused view, thus looking that a higher level node is centered. The root node in the left figure in the Figure 4.3 is centered in the hyperbolic tree in the way that radial tree visualization does. The right figure shows the layout after the user has repositioned the root node. In this layout, the node drawn bigger may seem to be "*root*" since node "Root", node "H01", and node "H02" are focused by similar degree lessening the perception of actual root node.

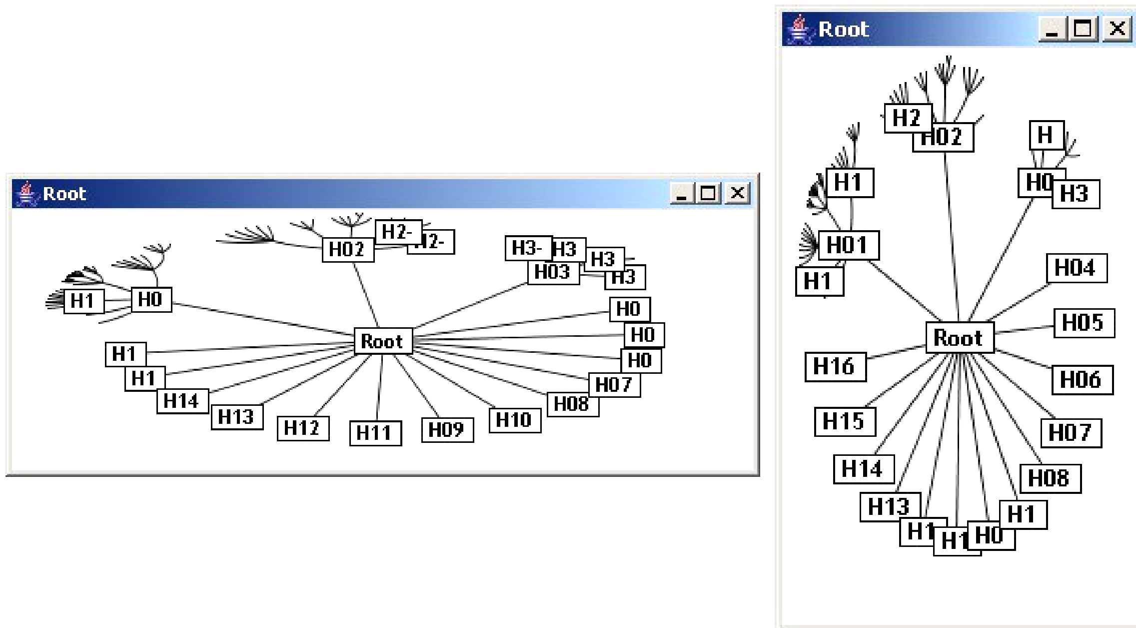


Figure 4.4 Hyperbolic tree layouts constrained by boundary conditions

This feature has both advantage and disadvantage. A user can place any node in the center without realizing whether an edge toward a parent node or toward a child node. This might help the analysis under the situation where forgetting the original hierarchy gives an opportunity to explore new relationship. It could be difficult to have a hierarchical sense after several node relocations drastically change the tree view.

Due to the geometric distortion approach, hyperbolic tree visualization does not require an extra optimization process found in some graph layout algorithms [2], enabling the interaction to be more stable. Consequently, layout changes from refocusing or hierarchy changes from modifying the guideline structure retain the general configuration appearance. The predictability maintained in the tree drawing helps users keep their mental maps of the hierarchy while they explore information with various branches of the tree. Furthermore, the property of hyperbolic geometry that the circumference of a circle on the hyperbolic plane grows exponentially with its radius provides exponentially more space as the hierarchy expands.

CHAPTER 5 CPG AUTHORING AND NAVIGATION

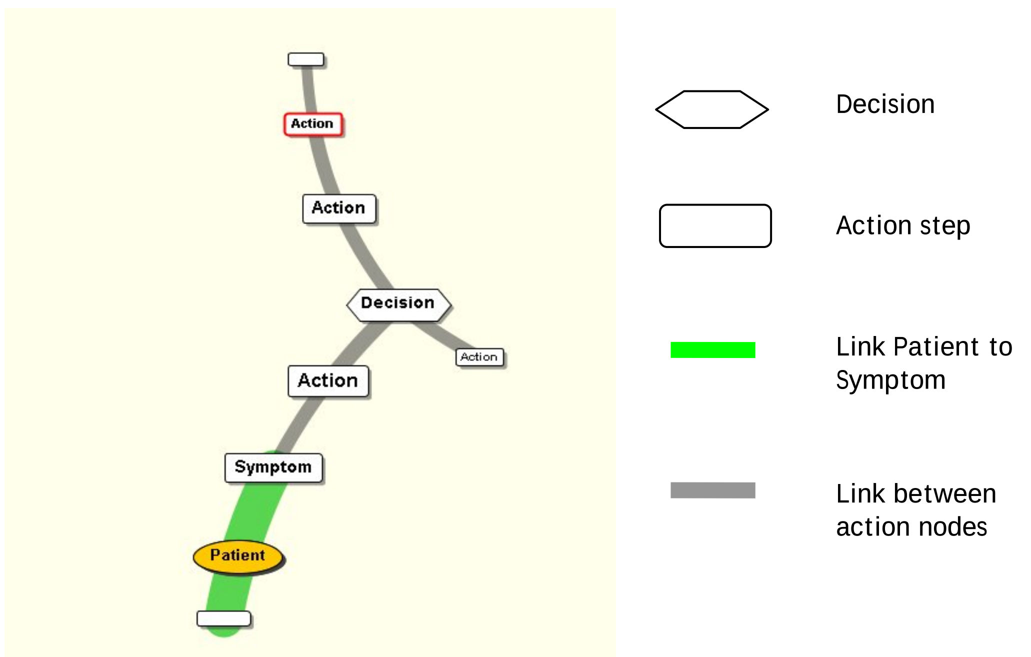
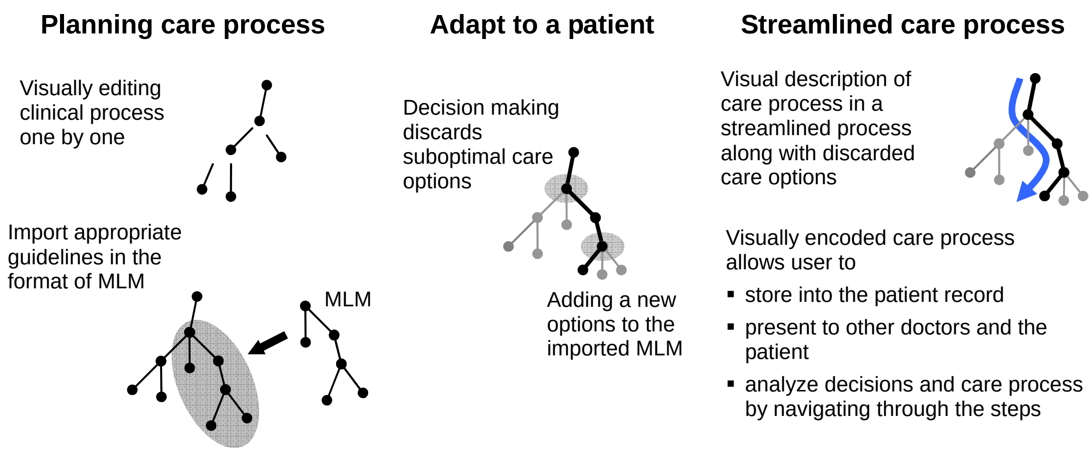


Figure 5.1 Basic authoring of CPG structure and CPG hierarchy components

This chapter illustrates how the interaction design accommodates the essential tasks for development, use, evaluate, and dissemination of CPG. Each of the following sections also introduces additional features that support the interaction design and discusses how those meet the criteria listed in Chapter 3.

5.1 CPG structure authoring



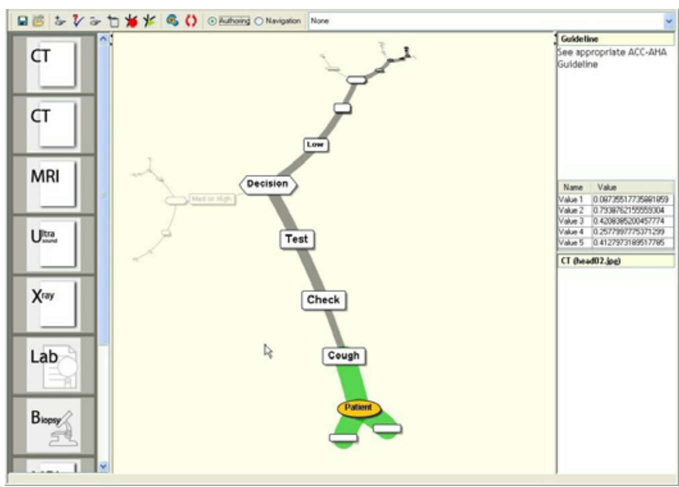


Figure 5.2 Streamlined patient care process after discarding suboptimal care options at decision nodes : The selected care process is drawn bold and darker, while discarded options are shown lighter.

The visualization shows the patient care process based on the symptoms found and the corresponding guidelines. As seen in Figure 5.1, the tree visualization places the patient at the root and a symptom connected to the root followed by a guideline related action corresponding to the symptom. The patient care planner edits the patient care

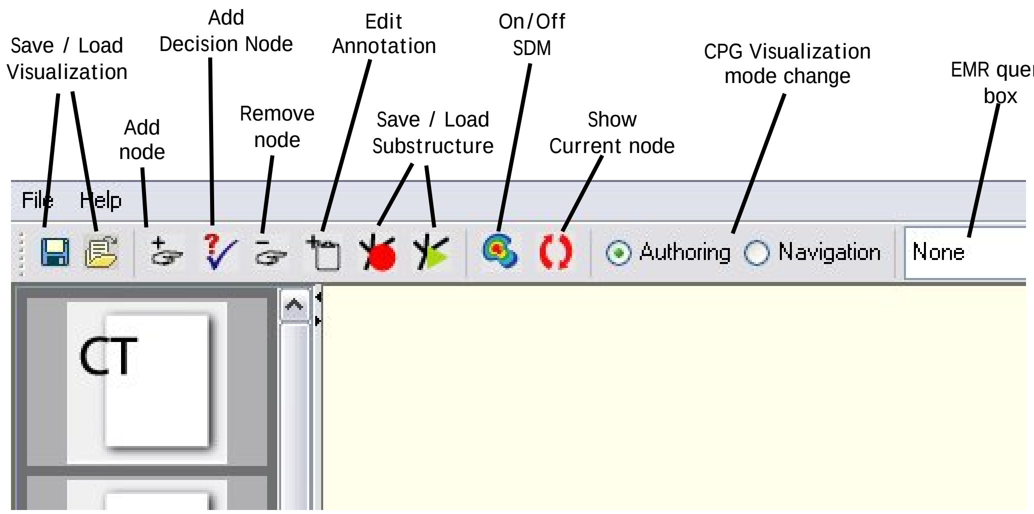


Figure 5.3 Tool list for CPG authoring and navigation

process by adding or removing a component or a structure of guideline (See Figure 5.2). The former is more commonly associated with development of a new guideline or refinement of a guideline to adapt to a specific care process. The latter corresponds to adding or deleting an existing guideline module to the care process. Users load or remove a guideline (which may be stored as an MLM) by inserting or removing a structure of graphical objects in the drawing. According to the care process, a user selects either root (patient) node or an action task node to which the new node will be connected. Whether a user adds a component or a substructure, the hyperbolic tree visualization does not drastically change its overall appearance due to the incrementally adjusting angles between the sibling nodes.

Following is a basic set of operations in editing CPG structure.

1. Addition of a node

a. By clicking a node, a user selects a node adding a child node. The selected node is highlighted with red line. The user pushes "*add node*" button in Figure 5.3. The tree model implementation independently managed in the visualization algorithm adds a child node model.

b. View model of the tree immediately recalculates a new layout from the root to every node under it and immediately refreshes the visualization.

2. Removal of a node

   a. By clicking a node, a user selects a node to be deleted. The selected node is highlighted with red line. The user pushes "*remove node*" in the Figure 5.3. The tree model evokes the removal of the selected node from the parent node model.

   b. The view model of the tree immediately recalculates a new layout of the tree from the root to the leaves and refreshes the visualization

3. Loading substructure

   a. A user selects a node to which a substructure will be added.

   b. The user pushes the "*load substructure*" button in the Figure 5.3.

   c. Step b. brings a file selection dialogue with which the user selects a structure file. Each of the file could be an individual guideline or just a decision structure.

   d. The tree model adds the substructure to the selected node model and recalculates the weight and node angles.

   e. The view model of the tree refreshes the visualization

4. Saving substructure

a. A user selects the top-most node of the substructure to be saved.

b. The user pushes the "*save structure*" button

c. Step b. brings a file selection dialogue that asks a filename.

d. The substructure is stored as a form of file.

5.2 Context-based Electronic Medical Record (EMR) integration and retrieval

Providing focused view in the paradigm of Focus+Context does not mean just geometrically scaling or visually highlighting visual objects as discussed in Chapter 4. Users should be able to get semantic focusing as well as geometric focusing, to be able to observe details of the selected task node. The hyperbolic tree visualization is enough to achieve the goal of visual focusing. However, the algorithm is based on the geometric property of the hyperbolic space, having nothing to do with clinical task specifics corresponding to the task nodes. The visualization technique needs another separate but coordinated scheme that shows semantic view of a node. The additional visualization should work well with the Focus+Context visualization. As a straightforward solution, creating a separate visualization screen can be considered to show semantic details of a focused node, but users have difficulty in recognizing the correspondence between what they are focusing in the tree visualization and the contents shown in the separate window. The only way that they recognize what to focus on is by recalling evocation of "focusing" or matching the node label attached to both the node and the window. It becomes more

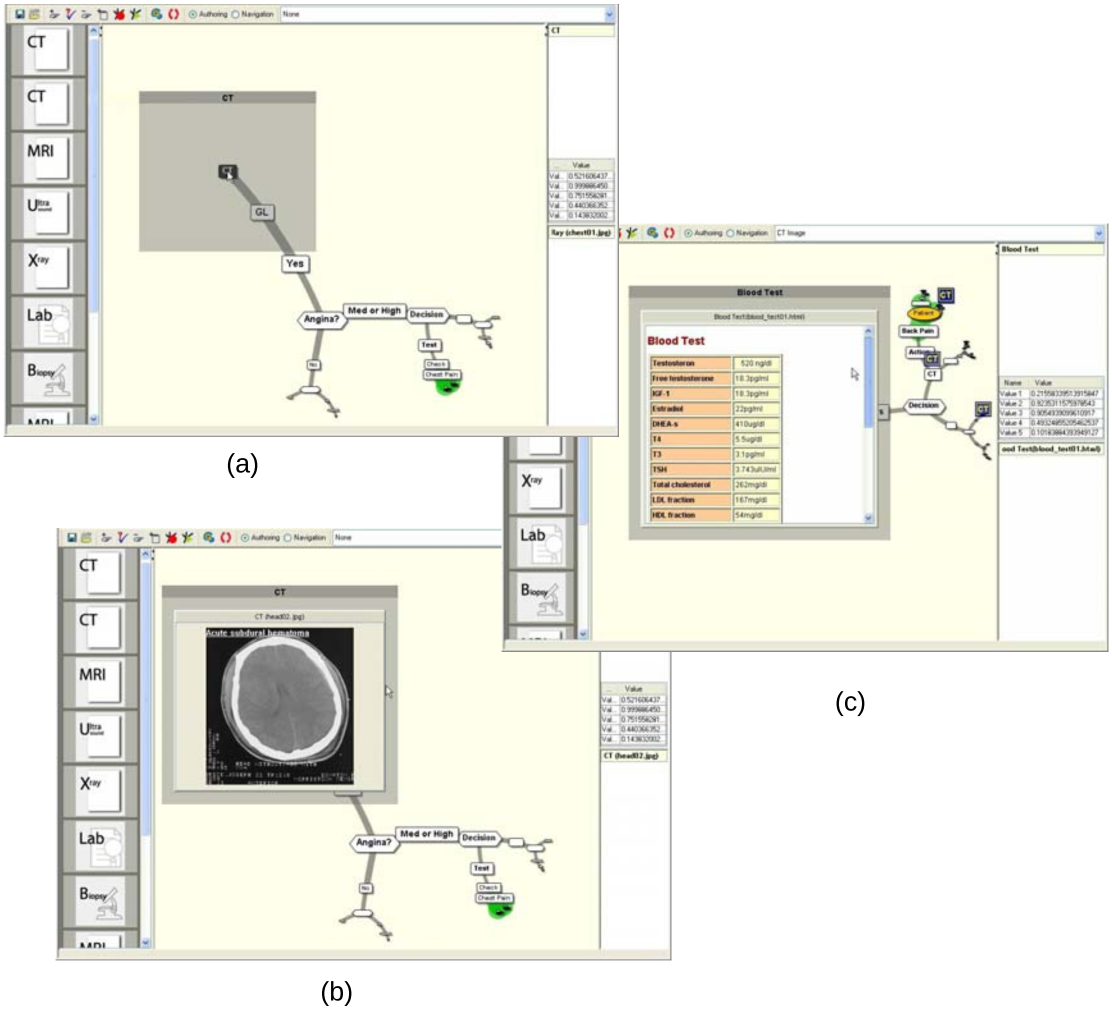


Figure 5.4 EMR integration into CPG visualization

serious problem especially for the situation where users deal with large number of nodes and contents, such as while navigating the structure and/or multiple contents needed to be shown simultaneously.

Nested interface can solve the above problem introducing additional space for showing the details. By user request, a node expands being smoothly converted to a pane and shows the task details inside of the node pane while still keeping the overall structure (see Figure 5.4). Though the nested interface is neither given by the geometry distortion nor seamlessly integrated, the expansion animation by growing its size from node to nested graph shows the contents as if they are integrated to the structure visualization. The interface is managed in a separate layer on top of the tree visualization layer.

The goal of the visualization system design is providing context first and then integrating/retrieving EMR to the visualization to provide more details within that context. Consequently, the visualization needs some way to represent the details incorporated with external sources.

The functional list of sub-criteria required to meet this objective includes the following: 1) the system should have integration of EMR information in the visualization (e.g. annotations of nodes) by simple user actions. 2) It should not change the perception of the tree visualization, which directly affects contextual understanding. 3) The connection between the details and nodes should be properly designed so their relationship is self-evident.

The system achieves these criteria through an expandable and retractable pane within the visualization that provides space for EMR information and other node annotation. As is seen in Figure 5.4 (a), the pane with node label “CT” is expanded and centered at the corresponding node in order to clarify the relationship. It is also transparent enough to allow the tree visualization behind the expanded pane to be seen. Expanded panes move with their associated nodes as the visualization changes as the focus shifts. Different types of EMR can be integrated into the expanded pane. In Figure 5.4 (a-c), leftmost pane in each screen shot shows EMR icons available for the patient. By simple drag-and-drop mouse action, users can integrate EMRs into the nodes in the tree. Documents written in HTML (Figure 5.4 (c)), images (Figure 5.4(b)), and videos are supported in the EMR integration. The top right and bottom figure shows integration of CT image and blood test result respectively. More than one EMR can also be placed into an expanded pane. Users can control the size of the pane and switch the view between the expanded pane and node object by a simple mouse click. As shown on the right side panes in Figure 5.4 (a-c), the system maintains a separate annotation note pane that contains the information corresponding to a selected node. A user can edit the annotations directly on this note pane.

5.3 Node contents layer

Focusing with hyperbolic tree shows details of structure. As discussed in the previous chapter, semantic details about a node should be brought up to users. Each pane is retractable and resizable. When it is expanded, it obscures the part of the tree visualization and thus user may lose the relationship between the node details on the expanded interface and the context shown behind the node interface. Guideline illustration of a node including patient-specific annotation by doctors can be contained in the node contents layer. In navigating through patient care process, users can retrieve EMR data and see it as a part of the visualization. Content driven navigation is also available, as users can query for the location of nodes with a specific type of EMR so that they can go to the nodes to analyze what has been done around each queried EMR element.

CHAPTER 6 - REPRESENTING SIGNIFICANCE DISTRIBUTION OVER THE STRUCTURE

6.1 Level of importance

Clinicians need to integrate levels of importance over the tree visualization. Features introduced in the previous sections all help users have more awareness of context and facilitate communication between medical practitioners. However, the tree visualization alone lacks information about the relative importance of the components of the CPG, because the tree visualization does not assign component weightings. To represent such interrelationships, quantitative information or ordinal information can be used to draw more attention to part of the care process or convey some additional information concerning the process itself. Encoding the information may include varying level of emphasis, significance, certainty/uncertainty, values given by decision methods, etc.

For example, a question, “Is it necessary for patient to have X-ray taken?” may arise during diagnosis and, to answer the question, the effect of this choice on decision rules applied at the next level of children nodes. If the impact of this choice is binary (it either completely determines subsequent decisions or has absolutely no effect on subsequent decisions), then the answer to the question is straightforward. Generally, however, there exists more than a single reasonable option, so that the decision is a selection process among alternative options available at the decision point, primarily based on ranked value for each of the alternatives [68]. Decision science methodologies address this by incorporating scoring of decision references or factors such as physical data, probability, sensitivity values, certainty values, and domain knowledge of users [69] into formal ranking metrics for the alternative options. This decision making analysis can be expressed within the hierarchical structure. The visualization of such clinical decision support (CDS) information helps clinicians not only understand a single decision but also appreciate its impact on future decisions and the overall care process.

To convey this CDS information, termed significance values in the visualization model engender several functional requirements. First, it needs to be shown together with the patient care process visualization. Second, it should be interactive and behave predictably as the visualization of the hierarchy changes. Third, visualized importance information should draw consistent visual attention even when nodes are shown shrunken to tiny visuals or while layout is being transformed. In other words, even if a user cannot distinguish a node in the tree visualization, its significance should be visually emphasized enough to draw attention in proportion to its significance, since it still contributes to the context of the structure in spite of the small size. This also facilitates the users recognizing the impact of a decision change on other significance values in the stream of care process.

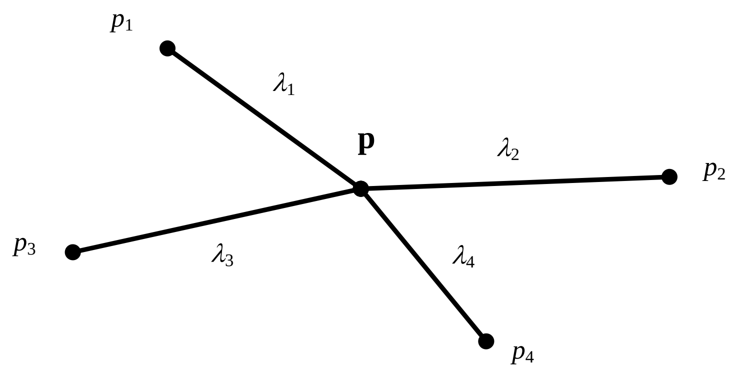


Figure 6.1 Spatial interpolation using *kriging* algorithm p is interpolated using sample p_i and weights λ_i

6.2 Significance Distribution Map

In order to address the above design criteria of the visualization, an algorithm based on a 2D spatial interpolation, *kriging* [70] was developed to interpolate significance values over the tree visualization. The importance value at every pixel position in the visualization is determined by *kriging* the significant values sampled at selected nodes and pixel distance to the selected nodes. The interpolated importance values on pixels are then transformed to color values. Throughout this dissertation the color map is referred to as s*ignificance distribution map* (*SDM*). This section explains *kriging* algorithm and how the algorithm is adapted to interactive use in the visualization system.

Consider an image space where every node is centered on a pixel location p_i and the pixel corresponds to a significance value U . We calculate decision value $\hat{u}$ for the pixel location p that is used for neither nodes nor edges, as shown in the Figure 6.1.

The *kriging* algorithm calculates decision value $\hat{U}(p)$ based on the sampled decision value $U(p_i)$.

$$\hat{U}(p) = \sum_{i=1}^{n} \lambda_i(p) U(p_i) \tag{6.1}$$

In the above equation (6.1), the interpolation is weighted sum of $U(p_i)$ and the algorithm calculates weight λ_i such that optimal weights minimize the mean square error between the interpolated value $\hat{U}(p)$ and actual value $U(p)$. In equation (6.2), the mean square error is

$$\begin{aligned} E\left(\left(\hat{U}(p) - U(p)\right)^2 \right) &= E\left(\hat{U}^2(p)\right) + E\left(U^2(p)\right) - 2E\left(U(p)\hat{U}(p)\right) \\ &= \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i(p)\lambda_j(p)\operatorname{cov}(p_i, p_j) + \sigma^2 - 2\sum_{i=1}^{n}\lambda_i(p)\operatorname{cov}(p, p_i) \\ &= \lambda^T(p)\mathbf{C}\lambda(p) + \sigma^2 - 2\lambda^T(p)\mathbf{c}(p) \end{aligned} \tag{6.2}$$

Where

$\mathbf{C}$: Covariance Matrix

$\mathbf{c}(p)$: Covariance vector between prediction vector p and sample location p_i

$$\lambda(p) = \mathbf{C}^{-1}\mathbf{c}(p) \tag{6.3}$$

Since a closer node will contribute more on the interpolation, the covariance matrix and the covariance vector is based on distance in hyperbolic geometry. What we would ultimately have here is λ s in equation (6.3). The weights are adjusted to minimize error between estimated and actual values. This establishes relationship between the significance value weight and pixel location *p*.

6.3 Interactive SDM visualization

While a user is transforming hyperbolic tree with SDM visualization turned on, continuous update of SDM is necessary. In order to achieve an interactive rate of visualization, special attention is paid to the sample node selection and the number of spatial interpolations performed. Theoretically, all the nodes contribute every pixel in the screen space, but SDM considers only nodes that will contribute more than predefined level to maintain the matrix size in equation (6.3).

As an additional approach to achieve interactive rate, the visualization control shows only a coarse level of SDM while the tree layout is being changed with user interaction such as navigation. When the user stops the interaction, the algorithm increases the level of detail incrementally showing the finer details of SDM to the pixel resolution level. The implementation generates two separate threads for hyperbolic tree visualization and SDM, with dependency controls between the threads, since SDM relies on the node position and overall hyperbolic tree layout calculation. Through this performance optimization, it is possible to achieve computationally affordable degree of interactive

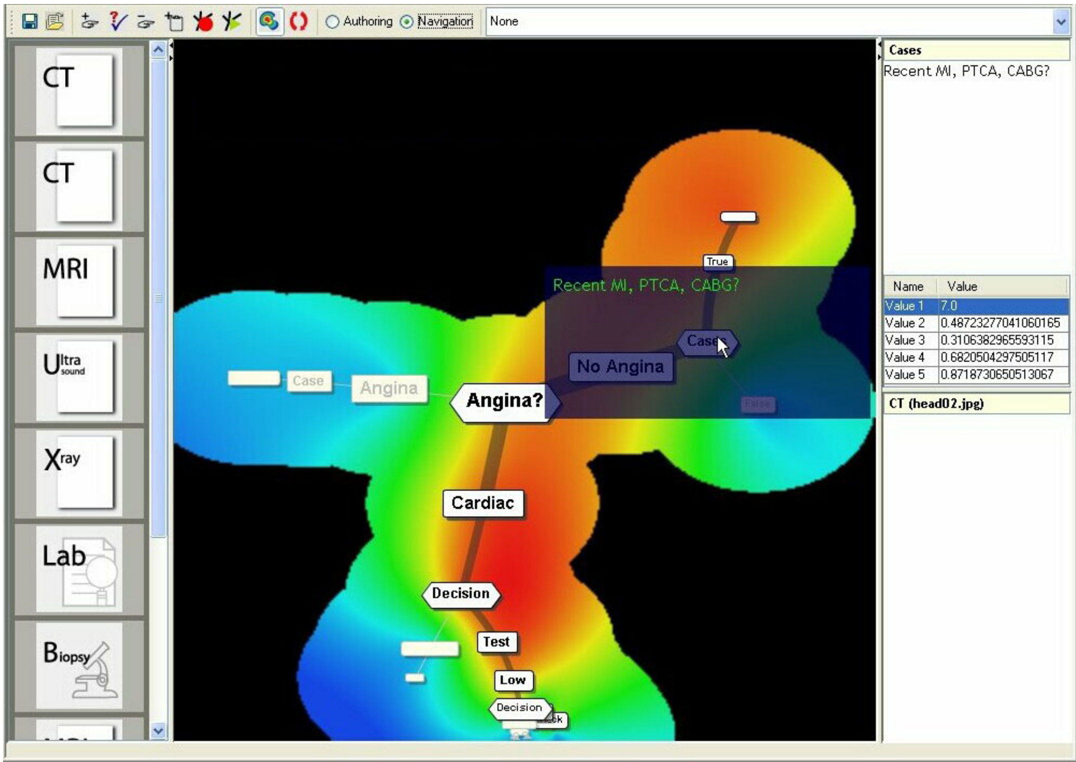


Figure 6.2 Screen capture of the CPG visualization system: Leftmost column of pane contains EMRs available for the patient. Rightmost column of pane contains annotation input panel where doctor type in their annotation. The context shown in the annotation pane is also shown in the pop-up panel right on the node. A table shown in the right pane shows 5 channels of significant values of the currently selected node. Value 1 is now shown in the SDM.

rate independent of the complexity of tree structure.

This SDM visualization in the system can selectively show as many as five dimensions of significance values and also allows users to change the attributes by manually changing significance value. This enables immediate visual updates necessary for noticing the different what-if situations. Alternatively, decision methods can feed different decision values to the significance values so that users are able to see both the direct and overall effects of a specific decision.

CHAPTER 7 SYSTEM

Figure 6.2 is a captured image of the system showing medical process visualization with SDM turned on for a patient case. The left pane lists icons of EMR entries available for this particular patient. The right pane shows annotation for the corresponding node. In navigation mode, the annotation is also shown superimposed over the patient care process visualization when a user places the mouse pointer over the node. By doing so, users can trace a stream of medical process seeing annotations.

Users work on this visualization system in two modes, authoring mode and navigation mode. In authoring mode, users edit patient care process by either manually adding or removing nodes, or loading clinical practice guidelines. In the navigation mode, users can also prune discarded substructures, but they are retained in lighter colors, to convey that those are not chosen but were considered in the decision. (See Figure 5.2)

In navigation mode, the system can be used to guide treatment or to perform post-event analysis of patient care. In the latter setting, it can be used to dissect out why a particular care process was chosen, along with the relevant EMR-based and CDS-based evidence. As such, it would be useful for both educational and quality improvement activities. By pushing a current status button as shown in the tool bar, the visualization

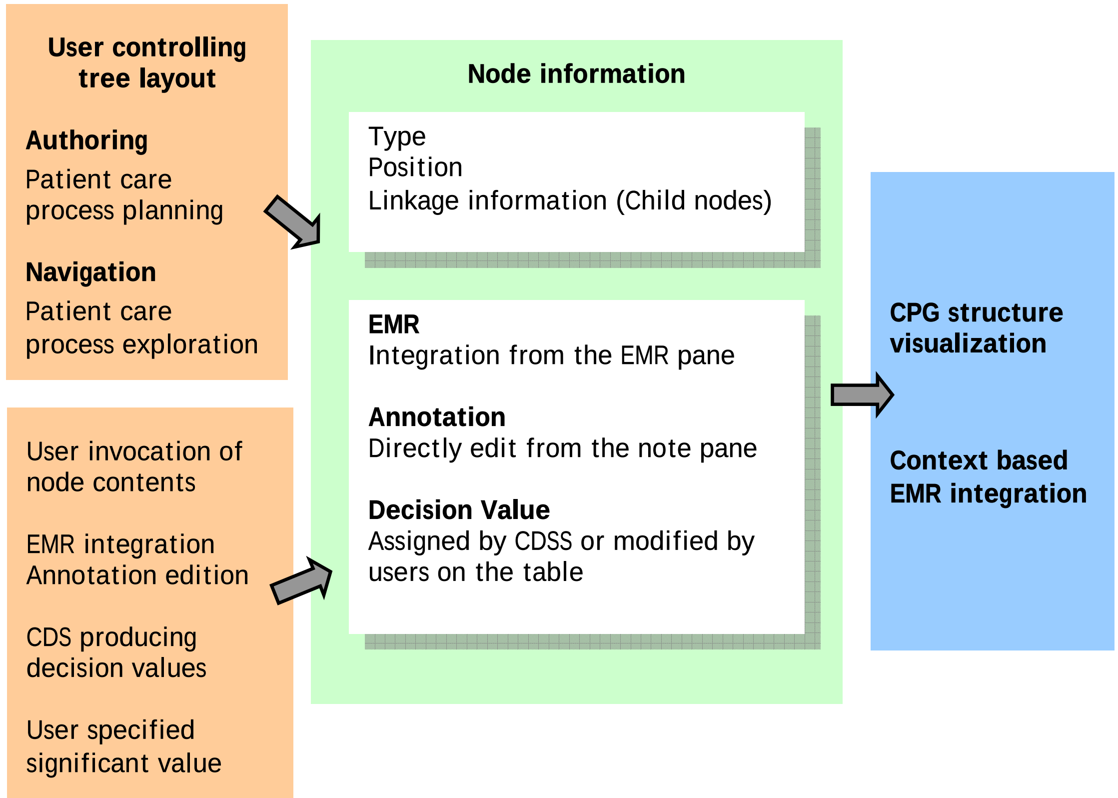


Figure 7.1 Implementation components diagram explained with user interaction

distinctively marks the node that indicates the current status. The clinicians may examine the past care process from the node and try to determine the preceding significant decisions. SDM visualization helps the doctor quickly focus on the critical decisions or results. Once the area is in focus, the doctor looks into the care process around key decision and can explore the further details of nodes. Overall user interactions are summarized in the diagram in Figure 7.1.

The visualization can also be a presentation tool of the health care outcomes to patient or other health care providers. Navigation and exploration features help clinicians demonstrate the underlying rationale of the care process accessible to non-experts, e.g.

patient. Without notably increasing the labor of clinicians working in the time-pressured environment, clinical evidences and logics are sufficiently and judiciously disclosed to the patient. The patient can be more empowered to collaborate with their physicians through the use of this "decision tool", which gets updated as the care plan progresses. The following section explains implementation of the introduced features. The usage of the visualization with examples is illustrated in the Appendix II.

7.1 Tree visualization implementation

Node position calculations in hyperbolic geometry and in screen space are separately done. Tree model manages node models with hierarchy information and each node model keeps the node information such as type, position, and linkage information to children node. The model also manages EMR linkage information, annotation texts, and decision values. The model data are then used to update the node view model by interpreting the type information to shape information, transforming the node position in hyperbolic geometry into the position in screen space considered with given properties (e.g. pane size), and traveling the substructure along the linkage information. Any changes in graph components require all the node position to be recalculated. Saving substructure stores the model information, which is independent of the viewing situation especially when it will be loaded later. Saving current visualization stores the comprehensive visualization information including the current node positions, expansion of node, etc. It will provide exactly same situation when user activity was paused and saved. Transmission of the current visualization allows providing synchronized view to the remote computer, which will be mentioned in the next chapter.

7.2 Nested node pane implementation

Drag and drop of an EMR icon will create a nested pane inside the node pane. Type information will decide the type of pane, for example, image pane, table pane, note pane, and video pane. More than one EMR pane can be nested in the node pane. The EMR panes in the node pane are evenly laid out with constraints. The constraints include the margin from the node pane boundary and gap between EMR panes. This layout decides the each of the EMR pane evenly. Wheel mouse motion adjusts the horizontal and vertical node pane size, and the nested EMR panes are then resized with the constraints. The EMR pane provides the scroll bar when the content size exceeds the node pane size. The combination of controlling the nested pane appearance will allow a user to have best look along with hierarchy visualization.

7.3 Interaction implementation

Switching on the SDM button, as depicted in the Figure 6.2, launches SDM visualization by controlling two threads for hyperbolic tree visualization and SDM visualization. Change in node position initiates the tread of SDM calculation starting from the coarsest level of four different levels and then incrementally continues to the finest level of the four levels. If change in node position occurs during the incremental calculation, the change reinitiates the SDM calculation with the new node positions again from the coarsest level. If a user changes significant value of a node, it also restarts SDM calculation to reflect the change in the SDM value. The listener model in the significant value table detects the change in value and triggers the SDM calculation.

CHAPTER 8 CONCLUSIONS AND FUTURE WORK

Taking non-streamlined note taking tool, as opposed to traditional verbal statement type of CPG, we provide a novel system that visually illustrates patient care process. The navigation features in the system provides intuitive learning tool guiding how guidelines are formed and patient care process should be done with the guideline. In use of this tool as patient care process, users can access to the related EMR with care process context in mind. Research efforts in medical informatics and information visualization played key roles to set criteria and design the system based on the question, how visualization will contribute the efficient use of medical knowledge in actual process of clinical care. The representations of CPG as a form of clinical knowledge and its actual adaptation to care process are visualized in straightforward way. The achievements of this work are listed below.

- The visualization provided a visual aid to seamlessly embody CPG into an actual care process. The visualization enables a visual-based organization of clinical knowledge, domain expertise, and evidences.

- Consistency is maintained from simple to complex hierarchy of visualization. The consistency provided a scalable ways for medical practitioners to perceive ever-changing care process information.
- Visual authoring and navigation accelerates the cycle of CPG development, use, evaluation, and dissemination.
- The supporting interactive tools enable other medical practitioners engaged in the care process to recall and/or recognize a given complex care process. SDM visualization conveys the information such as various levels of significance evoked by authors. Pop-up annotation panel is another example of combination of achieving clinical context while a user is navigating through the care process.
- The visualization can convey better described contexts to other medical practitioners.
- The visualization provides cohesive environment that links divergent evidences and information together. It also provides better product presentation tool regarding the care process as a health care product.

The visualization tool in this dissertation was not developed in attempt to replace any existing guideline formats such as GLIF, but this work will boost CPG development by alleviating problems induced by lack of usability in current implementations. This may be a tool that draws more attention to the use of guidelines and eliminates complicated and error prone procedures in CPG cycles.

Criteria have been carefully considered mostly for user interaction, but the usability test of the system should be studied to evaluate and improve the visualization design.

Addition of the temporal relationships between the guideline components might be a critical to enhance understanding of the patient care process in a timeline. Logical relationship in the current visualization implicitly shows temporal relationships, but a user cannot easily find how actions are arranged temporally, which may be critical for automatic triggering or alarming some of the actions that must be done in timely manner.

Making the visualization allowable in collaborative environment use is one of the further research and development to be done in the near future. Sharing visualization as well as understanding interaction between clinicians in remote environments will contribute clear decision exchange with little chance of communication errors. By providing a synchronized view to the several remote users over the network and allowing them to visually exchange CPG message, the visualization empowers efficiently sharing CPG or patient care process. Standardizing visual data exchange model needs to be studied and concerned security issues should be carefully considered. Even though the interaction design tries to minimize a number of widget uses, enabling users to directly manipulate the visual objects, the future implementation will seriously consider a new interaction design particularly for use of mobile computers such as Tablet PCs [71]. The pen-based interaction readily allows users to directly control the visualization screen and input annotation by handwriting and drawing without need to switch the interaction between the use of keyboard and mouse.

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APPENDIX I : IMPLEMENTING HYPERBOLIC GEOMETRY

The implementation of hyperbolic geometry uses the Poincaré model, because that makes translation between the underlying representation and screen coordinates straightforward. We represent a point A, at which geodesics cross as seen in the Figure 4.2 (a), in hyperbolic space by the corresponding point in the unit disk, Poincaré disk. The unit disk is represented with complex number of magnitude less than 1. Rigid transformations of the hyperbolic plane become circle preserving transformations of the unit disk. Any such transformation of point, node position, can be expressed as a complex function of z

$$z_t = \frac{\theta_z + P}{1 + \overline{P}_z}$$

Where P and θ are complex numbers, $|P| < 1$ and $|\theta| = 1$, and $\overline{P}$ is the complex conjugate of P. This transformation indicates a rotation by θ around the origin followed by moving the origin to P.

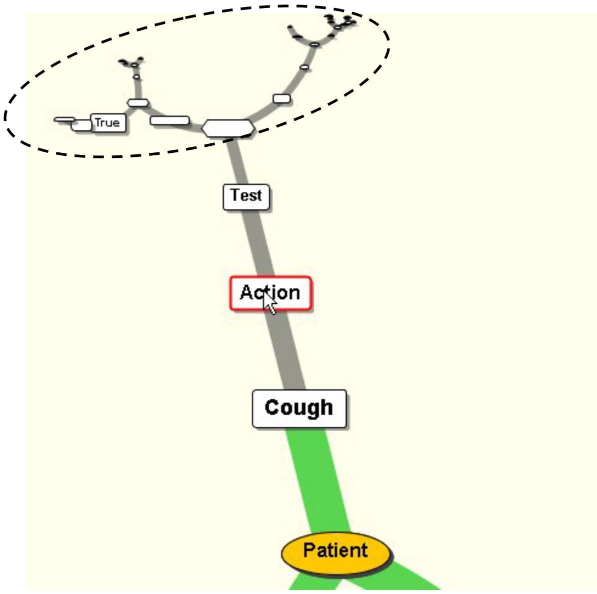
The actual transformation compositing the two is computed by,

$$P = \frac{\theta_2 P_1 + P_2}{\theta_2 P_1 \overline{P}_2 + 1} \qquad \text{and} \qquad \theta = \frac{\theta_1 \theta_2 + \theta_1 \overline{P}_1 P_2}{\theta_2 P_1 \overline{P}_2 + 1}.$$

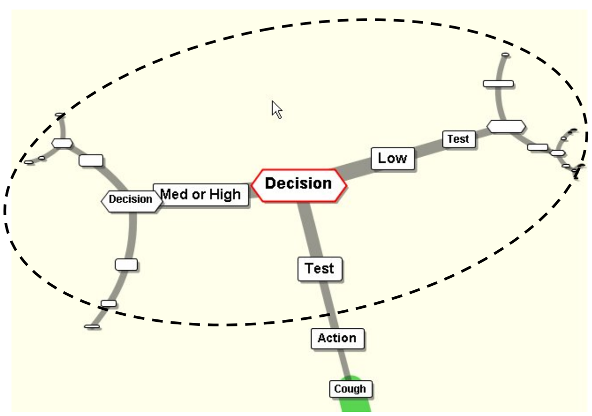
Normalization of θ to a magnitude 1 is always recommended when it is calculated, because round-off error accumulates errors in the magnitude.

APPENDIX II: USAGE EXAMPLE

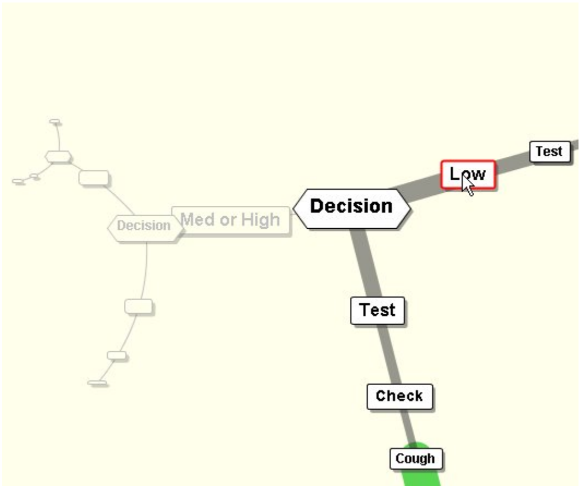
1 through 4 : Planning care process based on CPG'S



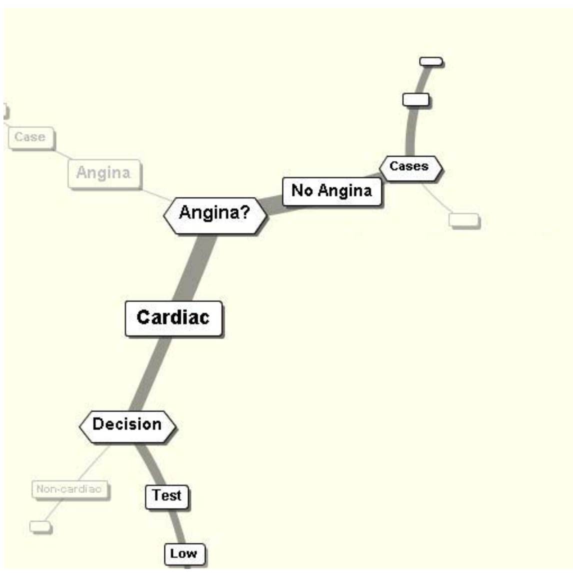
1. A clinician loads a clinical practice guideline to the patient node and sees the guideline in a contextual view of patient care.



2. As the user is dragging a decision node to the center of the visualization, the area described by dotted line becomes *focused* as seen in the left figure. The decision node and the surrounding structure are shown in detail. The user clicks a node and can see more information about the node in a separate side pane. The user can also edit the node information on the side pane.

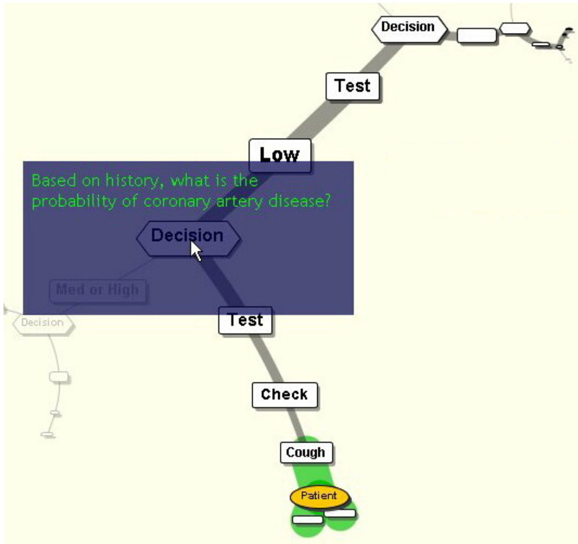


3. At the decision node, the clinician pruned the left substructure by selecting the right branch, thereby discarding the suboptimal care option in the left.

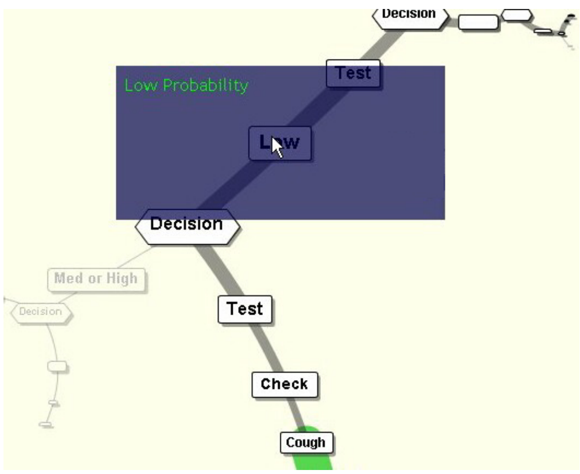


4. Further decisions have been made and the care plan is now shown as linear. Suboptimal care options are retained in lighter color, to indicate that those are not chosen but were considered.

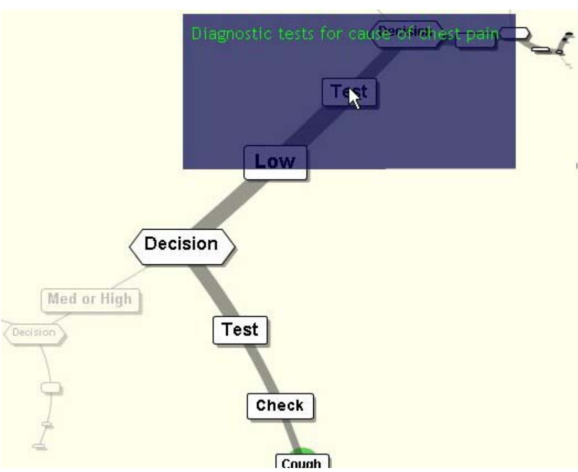
5 through 7 : Navigation of an established care process



5. Clinicians can learn or be reminded of the reasoning behind the care process by simply placing mouse pointer over the node. The transparent panel that pops up right onto the node shows the annotation of the CPG component. The annotation provides details/rationale used by the originator of this particular care process in making the decisions for this patient.



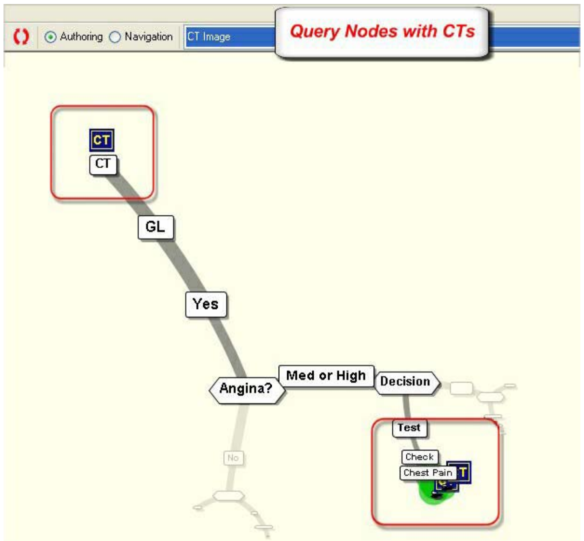
6. As the clinician moves the mouse point along the care process, annotations sequentially pop up.



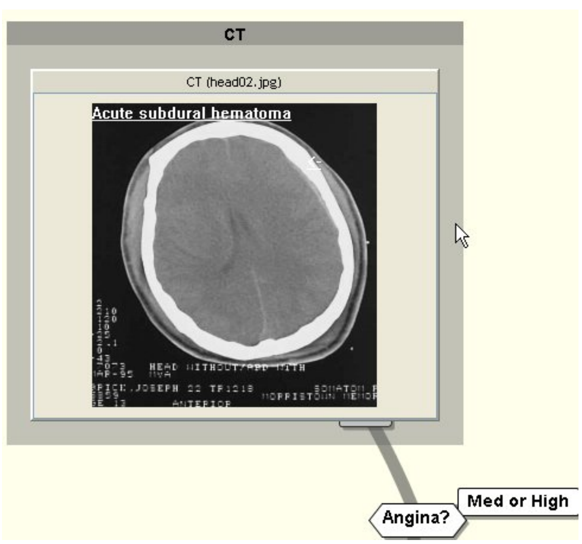
7. The care process visualization is still shown through the transparent annotation panel.

   As patient care proceeds, care providers can add annotations, EMR information, and updates to a node. Later, they can be retrieved directly from the node by simply placing mouse point or clicking on the node.

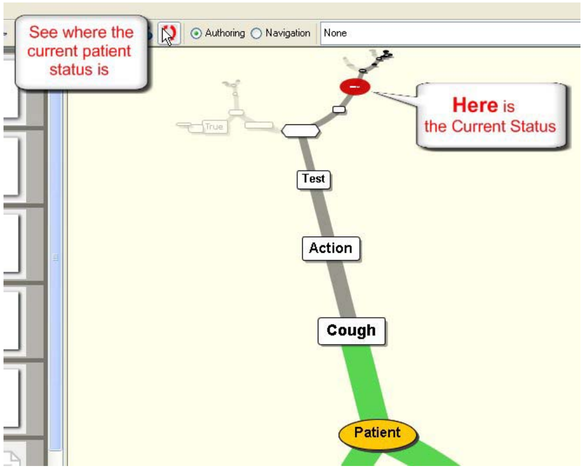
8 through 11 : Care process navigation based on query



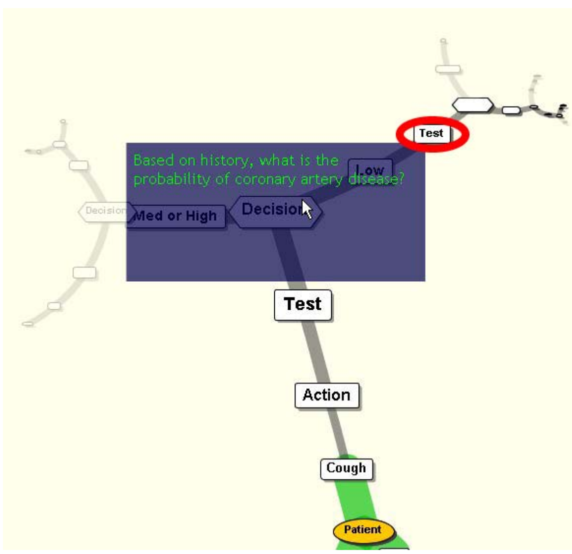
8. Given a visualization of a patient care process, a clinician may want to find some CPG components of the care process. If the clinician wants to see some CT images in the visualization, he/she needs to find nodes associated with CT image among the many nodes in the visualization. From the drop down menu, the clinician selects "CT image" and the nodes associated with CT images are now highlighted with blue label "CT" beside each node.



9. From the previous step, the clinician changed the focus on the one of the CT nodes. The clinician expands the node and sees the CT image, still maintaining the understanding of where the CT node comes from in the patient care process view.

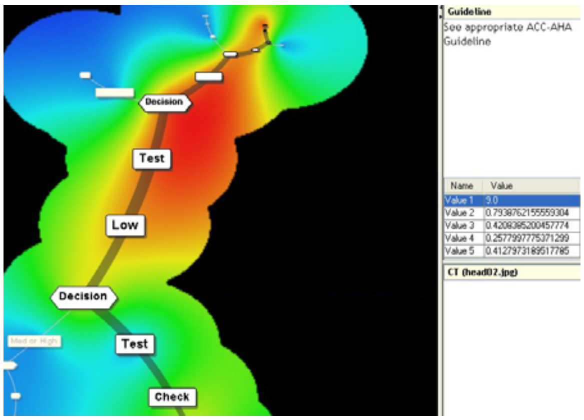


10. One of the most demanding tasks with the visualization is checking how the patient care is progressing. Clicking the “current status” button on the toolbar highlights the current node with blinking red mark.

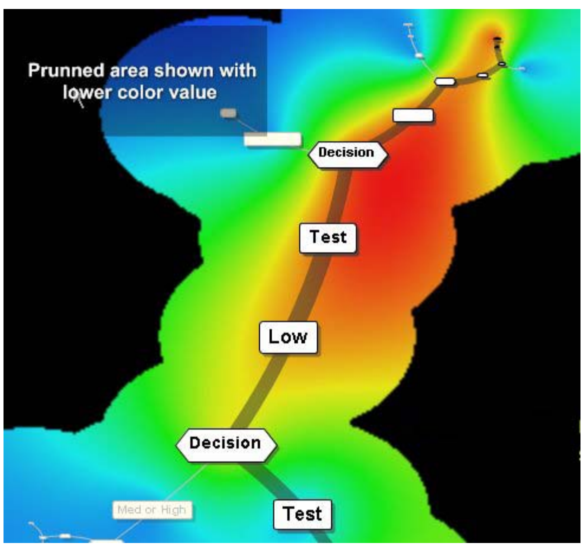


11. By focusing the current node area, the clinician can closely look into the past and future tasks from the current task. Again, the clinician can be reminded of the decision-making leading to the current task by placing mouse pointer over the decision node.

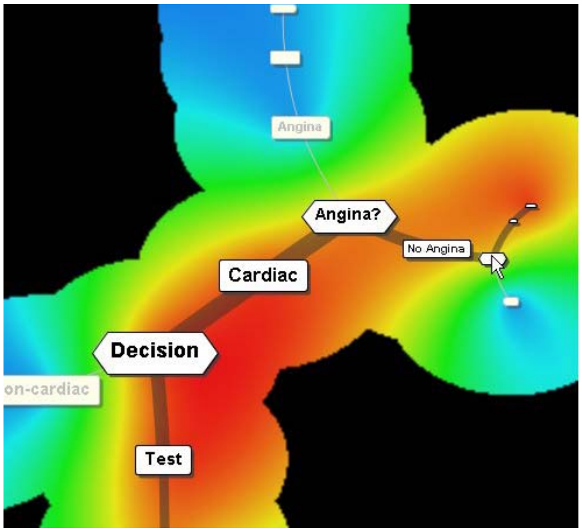
12 through 18 : SDM based care process navigation and user defined significance value encoding



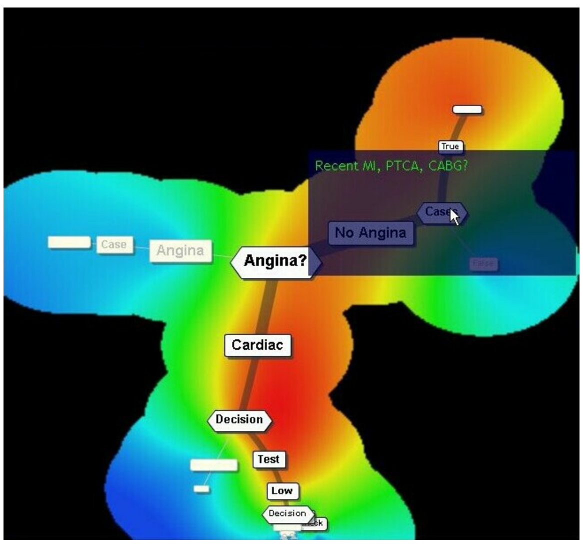
12. By turning on the SDM switch and, the clinician can see the significance distribution over the care process that previously was determined by weightings from a CDS or other clinician. More red color indicates relatively “more significant”, while more blue color shows “less significant”. Even though some nodes are shown tiny, the significance can be still observed with the red color over the surrounding area.



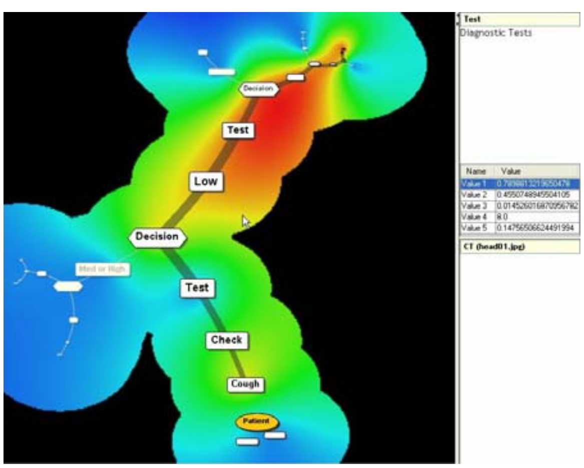
13. The area around pruned structures (suboptimal care options) as shown with lower color value.



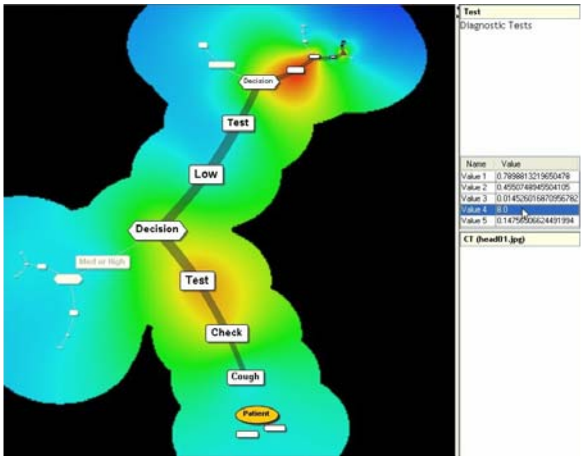
14. If the clinician wants to see the nodes that have the most significant impact on the patient's care plan, focusing the reddish area highlights the detail about these critical care processes.



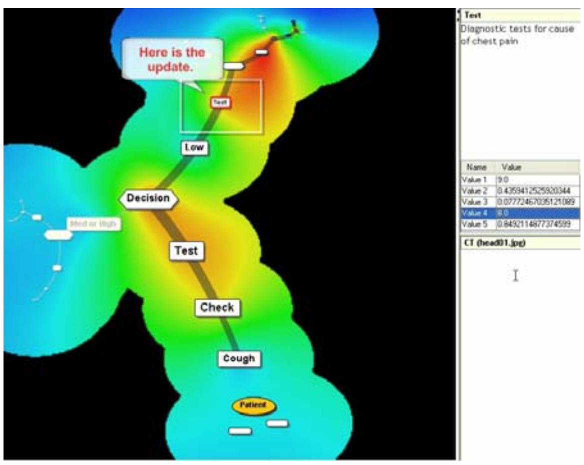
15. The clinician can drill down on the detail by placing mouse pointer on the node with navigation switch on.



16. Each node can have up to 5 alternative weighting values (e.g. – based on 5 different CDS models or manually generated by a clinician). The SDM can show the complete set of alternative values for each node, one of which is shown as the active value. Any of the values can be chosen, or edited, with the resulting changed SDM immediately generated for viewing.



17. Switching to other value (value number 4) shows different significant value distribution.



18. A clinician found that a node is underweighted and wants to change the value with one that he/she thinks of proper. The clinician modified the value and SDM immediately updates the change. The selected node (in the red rectangle in the left) got the more significance value, so the significance area has been expanded compared to the previous one.