

Contextual Adaptive Knowledge Visualization Environments

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Abstract: As an essential component of knowledge management systems, visualizations assist in creating, transferring and sharing knowledge in a wide range of contexts where knowledge workers need to explore, manage and get insights from tremendous volumes of data. Knowledge visualization context may incorporate any information in regard to the decisional problem context within which visualizations are applied, the visualization profiles of knowledge workers as well as their intended purposes. Due to the inherent dynamic nature, these contextual factors may cause the changing visualization requirements and difficulties in maintaining the effectiveness of a knowledge visualization when contextual changes occur. To address the contextual complexities, visualization systems to support knowledge management need to provide flexible support for the creation, manipulation, transformation and improvement of visualization solutions. Furthermore, they should be able to sense, analyze and respond to the contextual changes so as to support in maintaining the effectiveness of the solutions. In addition, they need to possess the capability to mediate between the problem and the knowledge workers through provision of action and presentation languages. However, many visualization systems tend to provide weak support for fulfilling these system requirements. They do not provide adequate flexibility for adapting the visualizations to fit different knowledge visualization contexts. This motivated us to propose and implement a flexible knowledge visualization system for better aiding knowledge creation, transfer and sharing, namely, Contextual Adaptive Visualization Environment (CAVE). CAVE provides flexible support for (1) sensing and being aware of changes in the problem, purpose and/or knowledge worker contexts, (2) interpreting the changes through relevant analysis and (3) responding to the changes through appropriate re-design and re-modelling of visual compositions to address the problem. In order to fulfil the requirements posed above, we developed and proposed conceptual models and frameworks which are further elucidated through system-oriented architectures and implementations.

Keywords: knowledge visualization, knowledge visualization context, knowledge creation and sharing, CAVE model, CAVE framework, and CAVE implementation

1. Introduction

Knowledge visualization is concerned with designing, implementing and applying appropriate visual representations to create, transform and communicate knowledge. Knowledge visualization is playing an increasingly important role in knowledge management systems (Burkhard, 2004; Cañas et al., 2005; Pinaud et al., 2006; Eppler and Burkhard, 2007; Bresciani and Eppler, 2009; Bresciani and Eppler, 2010; Eppler and Burkhard, 2011). Knowledge visualizations can be designed and developed by leveraging extensive visualization techniques and systems in the field of information visualization. The existing visualization techniques have been reviewed and categorized by researchers and practitioners according to their features such as data types that visualizations support, purposes that visualizations fulfil, and problem domains where visualizations are applied (Card, Mackinlay and Shneiderman, 1999; Chi, 2000; Chen, 2006; Spence, 2007; Heer, Bostock and Ogievetsky, 2010).

Visualizations can be applied to a wide range of contexts where people need to explore, create, represent, present, transfer and/or share knowledge. In general, knowledge visualization context incorporates the decisional problem context where knowledge visualizations are deployed, the visualization profiles of knowledge workers as well as their intended purposes to be achieved via applying the visualizations. More specifically, the decisional problem context may involve relevant problem situations, physical surroundings, time, knowledge visualization tasks and requirements, and social and technological contexts. The knowledge worker context may cover the knowledge workers' cognitive styles, personal preferences, prior knowledge of relevant problem domain(s), skill acquisition abilities, age, gender, etc. The purpose context describes the various and sometimes even conflicting goals and objectives that the knowledge workers attempt to achieve through applying the visualizations.

These contextual factors are diverse and dynamic, which, in turn, may cause huge complexity inherent in knowledge visualization context. As a result of this, the visualization requirements for solving the same decisional problem may vary when contextual changes occur. The same knowledge visualizations that are appropriate under particular problem and knowledge worker contexts might not even be relevant when certain contextual changes take place. For instance, knowledge workers of the same knowledge visualization may vary over time. Different knowledge workers may have different visualization preferences such as color, shape and interaction styles. Even for the same knowledge worker, the visualization requirements may change when the knowledge worker becomes more familiar with the relevant problem domain and the visualization system in use. A beginner-level knowledge worker often needs step-by-step support for how to manipulate visualizations while an expert-level knowledge worker may need more support for customizing visualization to complete sophisticated tasks.

Knowledge visualization context is complex and dynamic in nature, which may cause two major problems with developing effective knowledge visualizations. Firstly, many visualization systems to support knowledge management often have little concern on knowledge visualization context. Context complexity can significantly affect the effectiveness of a knowledge visualization in terms of how well it can support a knowledge worker to solve the decisional problem of interest and achieve the intended purpose. The lack of concerns on such impact may incur issues with ineffective knowledge visualization design and even visualization misuse. Secondly, there is a lack of support for developing and/or adapting knowledge visualizations to address the changing requirements caused by visualization context complexity. Though a knowledge visualization could be designed for a particular context, it can very soon get out of sync with respect to the context. Maintaining visualization effectiveness across contexts is a big challenge.

To address the above context-related problems, visualization systems to support knowledge management need to provide flexible support for creating, manipulating, transforming, improving and disposing visualization solutions. Meanwhile, they should support knowledge workers to flexibly adapt visualizations to address context dynamics and maintain the visualization effectiveness. However, many existing knowledge management systems and their visualizations tend to provide weak support for these requirements.

The above problems, issues and requirements associated with knowledge visualization context motivated us to propose and implement a flexible system for better aiding knowledge creation, transfer and sharing, namely, Contextual Adaptive Visualization Environment (CAVE). As illustrated in Figure 1, CAVE is a context-sensitive, adaptive platform that can provide flexible support for continuously sensing the dynamic problem, purpose and knowledge worker contexts. It assists knowledge workers to define the contextual changes through proper analysis and identify the associated visualization requirement changes. Also, CAVE helps the knowledge workers to respond to the changes and requirements through appropriate re-design and re-modelling of visual compositions to address the problem of interest.

In this paper, we introduce a framework of knowledge visualization context in section 2. We then proceed to explicate the definition of CAVE and its high-level functional requirements in section 3. Next, in section 4 we propose a conceptual model to deepen the understanding of CAVE definition and how it can address contextual complexities and the subsequent changing requirements. After this, a framework is proffered to guide the design and development of CAVE in section 5. In order to prove the validity of our proposed concepts, models and framework, we implemented a prototypical system to demonstrate how CAVE can adapt to both macro-level and micro-level contextual changes in section 6.

2. Knowledge visualization contexts

To illustrate and understand the complexity of context, many researchers have attempted to articulate and categorize contextual information, such as Dey (2001), Schmidt et al. (2000), Chen and Kotz (2000), Schilit, Adams and Want (1994), and Wu and Chen (2009). For instance, Schilit, Adams and Want (1994) identify three general contextual groups, i.e. computing context, user context and physical context. This classification scheme is further extended by Chen and Kotz (2000) with adding in two new groups: time context and context history. Building on top of these general context classifications and domain related context categorizations in mobile computing and adaptive geographical information systems (e.g. Petit, Ray and Claramunt (2006), and Nivala and Sarjakoski

(2003)), Wu and Chen (2009) proposed four contextual groups. They are context, activity context (i.e. task, tool and data), physical context (including location, orientation, physical surroundings, time, and movement state), and system context (i.e. system style and capability).

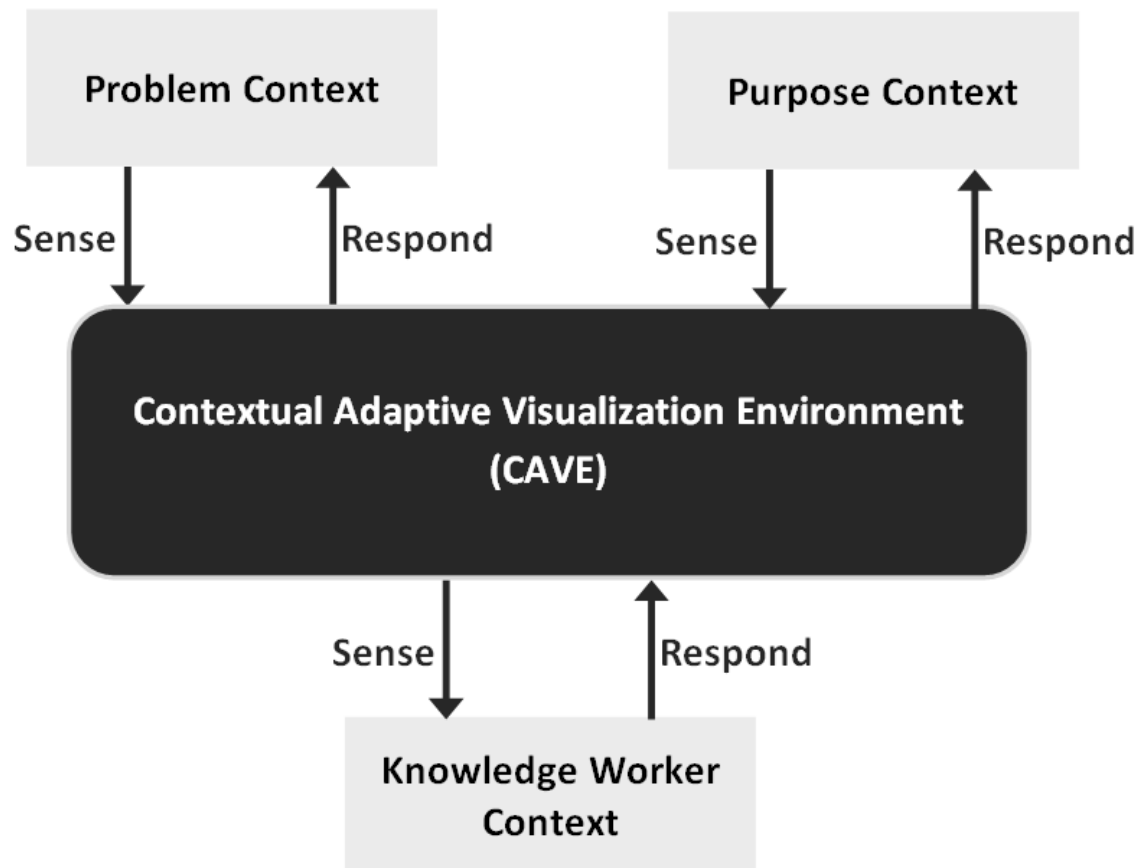


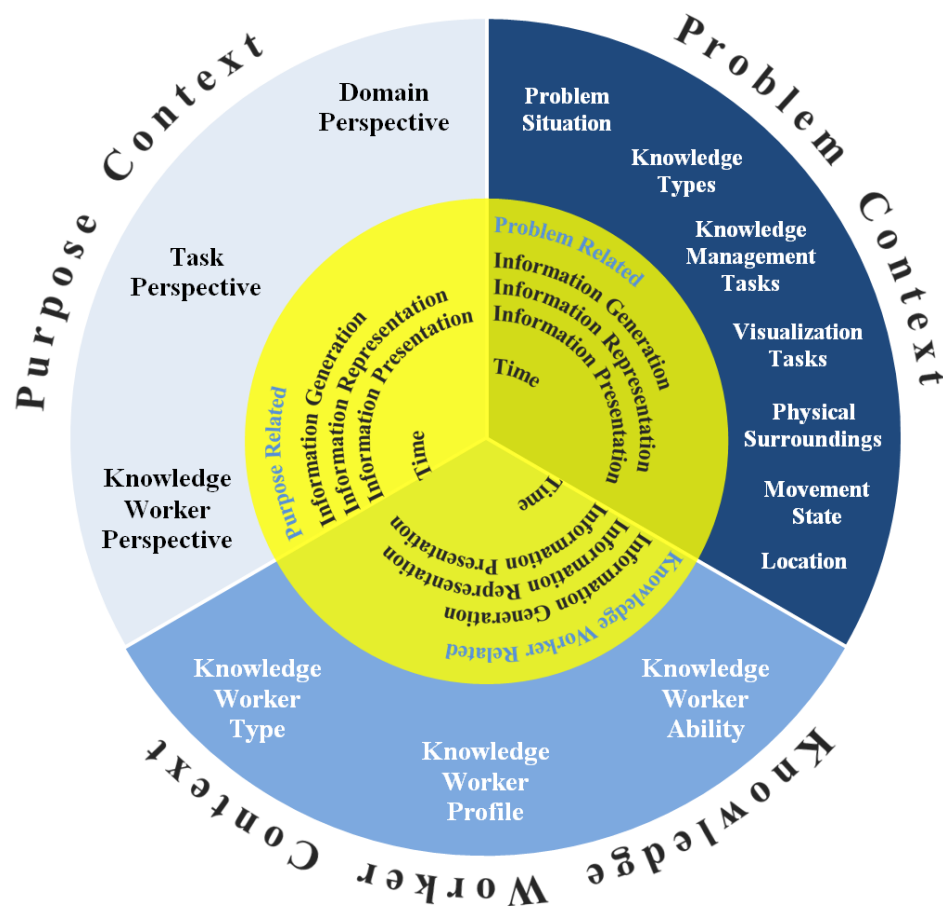
Figure 1: A high-level sense and response model of CAVE

In the domain of visualization, knowledge visualization context involves the information of any environmental entities that influence knowledge visualization design, development, application and evaluation. By reviewing and synthesizing the extant contextual classifications as well as the literature about visualization contextual information (e.g. Shneiderman (1996), Dreyfus and Dreyfus (1986), IBM Many Eyes (2011), Card, Mackinlay and Shneiderman (1999), Eppler and Burkhard (2007), Lee, Lee and Lee (2009), Stanford (2001), Donald et al. (2009)), we propose a Knowledge Visualization Context Framework (Figure 2).

As illustrated in Figure 2, we classify knowledge visualization context into three fundamental dimensions, that is, the decisional problem context within which visualizations are deployed, the situational context of knowledge workers, and the purpose(s) which the knowledge workers attempt to achieve via applying the visualizations. Each dimension consists of a set of contextual categories. There are four common contextual categories that are shared among these dimensions, i.e. knowledge generation, knowledge representation, knowledge presentation, and time. Detailed information about these contextual dimensions and their potential impact on knowledge visualization design and implementation are presented in sub-sections 2.1-2.4.

2.1 Problem context

This problem dimension is concerned with the contextual information with regard to the problem situation to be supported and potential solutions. A brief summary of typical contextual factors involved in problem dimension and categories is provided in Table 1.

**Figure 2:** Knowledge visualization context framework**Table 1:** Problem context

Contextual Dimension	Contextual Categories	Description & Example
Problem Context	Problem Situation	E.g. Statistical and categorical data management, digital library management, personal services support, complex documents management, history management, classifications management, networks management, etc.
	Knowledge Types	Declarative knowledge, procedural knowledge, experiential knowledge, people-related knowledge, location-based knowledge, scenario-based knowledge, and normative/value-based knowledge
	Knowledge Management Tasks	Knowledge creation, codification, transfer, identification, application/learning, measurement/assessment, and signaling
	Visualization Tasks	Overview, zoom, filter, details-on-demand, relate, history, and extract
	Location	E.g. latitude, longitude, altitude, city, suburb, country, etc.
	Physical Surroundings	Lighting, temperature, surrounding landscape, weather conditions, noise levels, etc.
	Movement State	E.g. Speed
	Knowledge Generation	Data transformation requirements of a decisional problem
	Knowledge Representation	Data type, data quality, data volume, and relevant techniques (e.g. structured text/tables, mental images/stories, heuristic sketch, conceptual diagram, image/visual metaphor, knowledge map, etc.)
	Knowledge Presentation	Semantic layer, animation, interaction, output device (size, resolution), input device (touch panel, keyboard, mouse, etc.), network connectivity, and communication costs/bandwidth
	Time	Time-series data involved in a decisional problem, when the effectiveness of a visualization solution is confirmed, etc.

Knowledge visualizations nowadays may be employed in many problem domains and/or disciplines to support diverse user purposes and tasks involved in information/knowledge navigation, retrieval, query, discovery and/or interpretation. For example, Card et al. (1999) have identified seven representative domains, namely, statistical and categorical data management, digital library management, personal services support, complex documents management, history management, classifications management, and networks management. Quite often, real-world decisional problems span multiple application domains, instead of merely residing within a single domain. For example, in a large utility (e.g. electricity and gas) infrastructure company, the senior management may be interested in exploring and visualizing the patterns and/or trends embedded in the problematic gas and electricity connections (on maps) which have incurred exceptionally high maintenance costs. This issue covers three typical application domains, that is, statistical and categorical data management, complex documents management, and networks management. More specifically, the application domain of statistical and categorical data management is involved due to the need of visualizing accounting data (i.e. maintenance costs of electricity connections and gas pipelines). Complex documents management is required to handle the reports of electricity connection and gas pipeline faults. Networks management is a necessity for effectively generating map-based electricity and gas networks with problematic connections highlighted.

2.2 Knowledge worker context

The knowledge worker dimension incorporates any stakeholder related aspects that can affect the design, development, cognition, interpretation and/or evaluation of a visualization by different types of stakeholders. Representative contextual factors relating to this dimension are summarized in Table 2.

Table 2: Knowledge worker context

Contextual Dimension	Contextual Categories	Description & Example
Knowledge Worker Context	Knowledge Worker Type	E.g. individual, team, community of practice, organization and the public
	Knowledge Worker Profile	Cognitive styles, personal characteristics and preferences, educational background, culture and social background (faith, nationality, etc.), personality (introversive/extroversive), physical condition (disability, left/right hands, etc.), age, gender, mood, etc.
	Knowledge Worker Ability	Prior knowledge (e.g. knowledge in the problem domain, past experience with manipulating the visualization, past experience with using the visualization system), skill acquisition ability (i.e. novice, advanced beginner, competent, proficient, expert, and master levels), etc.
	Knowledge Generation	Data transformation requirements of a knowledge worker
	Knowledge Representation	Data type, data quality, data volume, and relevant techniques
	Knowledge Presentation	Semantic layer, animation, interaction, output device, input device, network connectivity, and communication costs/bandwidth
	Time	Time-series data associated with a knowledge worker, e.g. when a visualization solution is effective for the knowledge worker, etc.

Along the way of accomplishing various user tasks involved in the associated problem domains, knowledge workers may go through six principal stages of learning or skill development through which they progress to achieve higher levels of proficiency and expertise (Dreyfus & Dreyfus, 1986). These fundamental learning development stages are novice, advanced beginner, competent, proficient, expertise and master. Each of the above learning development stage is also associated with six mental functions, i.e. similarity recognition, aspect recognition, decision paradigm, perspective, commitment, and monitoring. These learning development stages and mental functions form the building blocks of the skill acquisition model proposed by Dreyfus and Dreyfus (1986).

As going through the learning development stages from novice to master, knowledge workers gradually develop their abilities of resolving new problems through recognizing the similarities between the new problem situation and previous problem situations that they have experienced. This, in turn, enables them to gain stronger problem solving and decision making capabilities and better performance. Knowledge workers with different abilities at different learning development stages may have different sets of tasks to complete so as to address certain problem issues of interest and/or achieve certain purposes, which can lead to different requirements for visualizations.

More specifically, according to Dreyfus and Dreyfus (1986), people at beginner levels are only capable of perceiving and understanding simple clues in a problem context and recognizing very limited similar features to their experienced problems. They have to depend on the available relevant rules and directions for guiding their activities, and on deliberately monitoring their own performance and getting feedback. The lack of guidance on performing certain tasks or the lack of previous experiences for resolving relevant problems may cause them to present low performance. In contrast, people with higher levels of expertise often have stronger capabilities to understand and resolve problems though basing their judgments against past experiences and relevant knowledge, which often leads to a better performance (Dreyfus and Dreyfus, 1986). They are more likely to cope with complex problems and see through complicated situations, decide task requirements for resolving the problems, and perform the tasks with less monitoring efforts and more commitment to problem solving activities.

2.3 Purpose context

The purpose dimension contains contextual information about what a knowledge worker is trying to achieve through applying visualizations in a particular domain to address/accomplish certain problems/tasks. Table 3 outlines the typical contextual factors involved in the purpose context.

Table 3: Purpose context

Contextual Dimension	Contextual Categories	Description & Example
Purpose Context	Domain Related Purpose	E.g. to support statistical data analysis, to manage digital libraries, to provide personal services support, to manage complex documents, to aid historical data management, to manage classifications, to visualize networks, etc.
	Knowledge Worker Related Purpose	E.g. to support financial analysis of last year, to support education and E-learning in the University of Auckland, to support military debriefing, etc.)
	Task Related Purpose	E.g. to discovery relationships/patterns from a large volume of data points, facilitate data comparison, track/display trends over time, illustrate structure or composition, analyze words/texts, and explore geographical data
	Knowledge Generation	Data transformation requirements for achieving certain purposes
	Knowledge Representation	Data type, data quality, data volume, and relevant techniques
	Knowledge Presentation	Semantic layer, animation, interaction, output device, input device, network connectivity, and communication costs/bandwidth
	Time	Purpose related time data, e.g. when a purpose becomes relevant

The purpose context involves three essential perspectives, that is, application domain, knowledge, and task related purposes. The knowledge worker perspective specifies visualization purpose from the angle of what objectives knowledge workers attempt to achieve via the visualization within their specific context. The task perspective depicts the visualization purpose from the angle of what user tasks a knowledge visualization aims to support. The domain perspective defines the visualization purpose from the angle of what in general the visualization is trying to fulfil within its particular application fields/contexts. In addition, purpose context incorporates information and requirements of purpose related information generation/representation/presentation and time.

2.4 Contextual impact on knowledge visualization design and implementation

The changing and dynamic problem, purpose and knowledge worker contexts may lead to changing visualization requirements. For example, knowledge workers at beginner levels can normally deal with smaller chunks of data at one time and thus require visualization designs containing the support/guidance for basic operations to accomplish a particular task. Compared to them, knowledge workers with higher levels of expertise are often able to process relatively large chunks of data. They may not need visualizations to provide basic operation guidance but rather the support for more complicated tasks such as advanced information analysis.

Furthermore, the problem, purpose and knowledge worker contexts may significantly influence the design and implementation of visualizations in knowledge management systems. For instance, knowledge visualization development is intimately coupled with mental tasks and attributes

associated with different learning development stages. Knowledge visualization design and implementation should concern to what extent the knowledge workers rely on clearly defined decision making rules or task instructions, how well they are aware of the underlying problem situations, how easily they can recognize similarities between the problem under investigation and the problems that they resolved in the past, how accurately they may identify and understand the relevant task requirements from the similarities, and how effectively they can monitor their own performance. In addition, the visualization system involved in knowledge management should offer adequate support for personalization and customization so as to better serve different knowledge workers. Knowledge management systems should also provide appropriate adaptability mechanisms to assist the knowledge workers with their transition from beginners through to masters/experts. To address the complexities involved in knowledge visualization context, we introduce contextual adaptive visualization environment in the following section.

3. Contextual Adaptive Visualization Environment (CAVE)

We define a Contextual Adaptive Visualization Environment as a context-sensitive, adaptive platform that helps knowledge workers to continuously monitor the changing/evolving context of their interested problem, sense and analyze the changes in the context, and respond to the problem by utilizing data, models (problem and visual), solvers and scenarios to create and manage effective visual compositions (Figure 3). The responses by the system and by the knowledge worker could be at different levels. It could be a parametric change (single loop learning), introduction/modification/deletion of variables of model (double loop learning), and/or transformational changes at a deep and broad level (triple loop learning). The key purpose of CAVE is to sense, analyze and respond to the changes in the visualization contexts. Furthermore, CAVE mediates between the problem and the knowledge workers through the explicit provision of action and presentation languages. To address the contextual complexities, CAVE provides flexible support for (1) creating/manipulating/transforming/improving/disposing visualization solutions and (2) maintaining the effectiveness of the solutions within the changing/evolving problem context. This definition of CAVE raises many requirements and features which are elucidated in the following sub-sections 3.1-3.4.

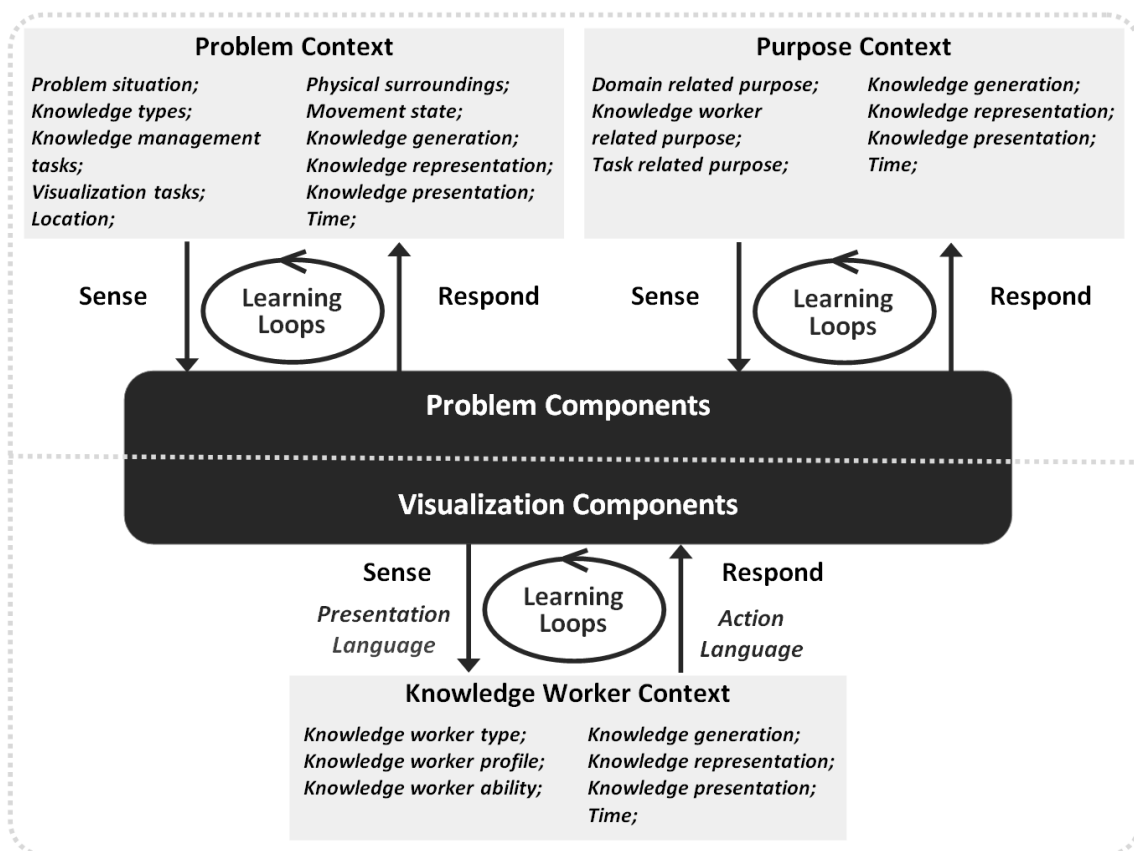


Figure 3: Contextual adaptive visualization environment model

3.1 Visualization creation

To ensure that visualizations can match the problem, purpose and knowledge worker contexts, new visualizations are often required to support various tasks. Accordingly, knowledge visualization systems need to enable a knowledge worker to build new visualizations in a flexible fashion. The knowledge worker should be able to develop new visualizations either from scratch or based on existing reusable visualization components. As demonstrated in Chi and Riedl's (1998) data state model, this requirement can be achieved by selecting and integrating appropriate within-stage and between-stage operations. Systems fulfilling this requirement may significantly enhance the knowledge worker's capability of handling the changing visualization purposes and contexts.

3.2 Visualization modification/customization/enhancement

The changing and evolving knowledge visualization contexts often lead to varied visualization requirements, which, in turn, require knowledge visualization systems to enable users to flexibly modify/customize/ enhance visualizations. A visualization, which can fulfil a particular purpose at one point in time, may not be able to achieve the same level effectiveness when the visualization stakeholders, purposes and/or contexts change over time. Thus, knowledge visualization systems need to offer users the capabilities of flexibly modifying, customizing and enhancing visualizations so as to meet the changing requirements.

This requirement can be further clarified by applying Chi and Riedl (1998)'s data state model. Chi (2000) opined that a visualization technique can be decomposed into a set of data stages and operations. Data operations are composed of within-stage operators (i.e. value, analytical and visualization stage operators) and between-stage transformations (i.e. data, visualization and visual mapping transformations). Visualization modification/customization/ enhancement can be conducted through adjusting these within-stage and between-stage operations, e.g. selecting the desired visual representations, changing the colour or the hue, adjusting transformation parameters, etc.

3.3 Visualization integration

This requirement is concerned with flexibly combining the visual contents generated by different visualization techniques so as to present a rich view of the underlying data. Due to the changing visualization purposes, contexts and stakeholders, visualizations are often required to reveal different features of the source data. However, visualization techniques have their specific focus on handling particular types of data and reflecting particular features of the source data (Chi et al., 1997). In other words, no single visualization technique can be effective for addressing all data types and/or all visualization purposes. Therefore, integrating multiple visualization techniques within a single visualization system becomes a natural and effective way to assist users in exploring more features of the source data (Hibbard, 1999). Visualization integration may need to be performed against a single data source or multiple sources.

3.4 Visualization transformation

Besides creating and customizing visualization techniques, visualization transformation is equally important for maintaining the effectiveness of a visualization in terms of fulfilling a certain purpose. It requires visualization systems to allow users to transform visualizations from one type to another in a flexible and seamless manner with the minimum amount of effort required. This will enable the users to visualize the same set of data through different visualization techniques and observe different features/views of the data.

In order to fulfil the requirements posed above, we developed and proposed a CAVE framework (section 4) which is further elucidated through an implementation (section 5).

4. Contextual Adaptive Visualization Environment framework

The Contextual Adaptive Visualization Environment (CAVE) framework builds upon the CAVE model discussed in the previous section. As illustrated in Figure 4, a knowledge visualization solution comprises four fundamental building blocks, that is, data, models, solvers and scenarios. These building blocks together assist a knowledge worker in translating a decisional problem into a form that is recognizable and manageable by CAVE and ultimately by a knowledge worker. This understanding enables the knowledge worker to create visualization oriented data, models, solvers and scenarios

and adapt them into a form that effectively responds to the contextual changes. These components are managed and connected together by a central component – kernel – which enables the communication among different components. All these components cooperate together to help with various tasks involved in knowledge generation, knowledge representation, knowledge presentation, visualization interaction and visualization evaluation.

CAVE may incorporate two broad types of data, that is, user data required by the system execution, and the data depicting the characteristics of problem, purpose and knowledge worker contexts. They also involve two essential groups of models for accomplishing knowledge creation and visualization. Accordingly, there are two types of solvers for manipulating their corresponding type of models. Data, model and solver can be integrated to form a scenario. Among these CAVE components, the problem related data, models, solvers and scenarios are used to generate knowledge while the visualization technique related components manages the representation and presentation of the knowledge. More specifically, the problems related components are responsible for enhancing the quality, relevance and effectiveness of the source data in terms of how well they can address the decisional problem of interest. In contrast, the visualization technique related components define and manage the way of how the ready to be visualized data sets are transformed into appropriate views so as to adapt to the dynamic contexts. A knowledge visualization solution is made up of appropriate problem and visualization technique scenarios.

This framework is used to guide the design and implementation of a contextual adaptive visualization environment, which is further elucidated in the subsequent section.

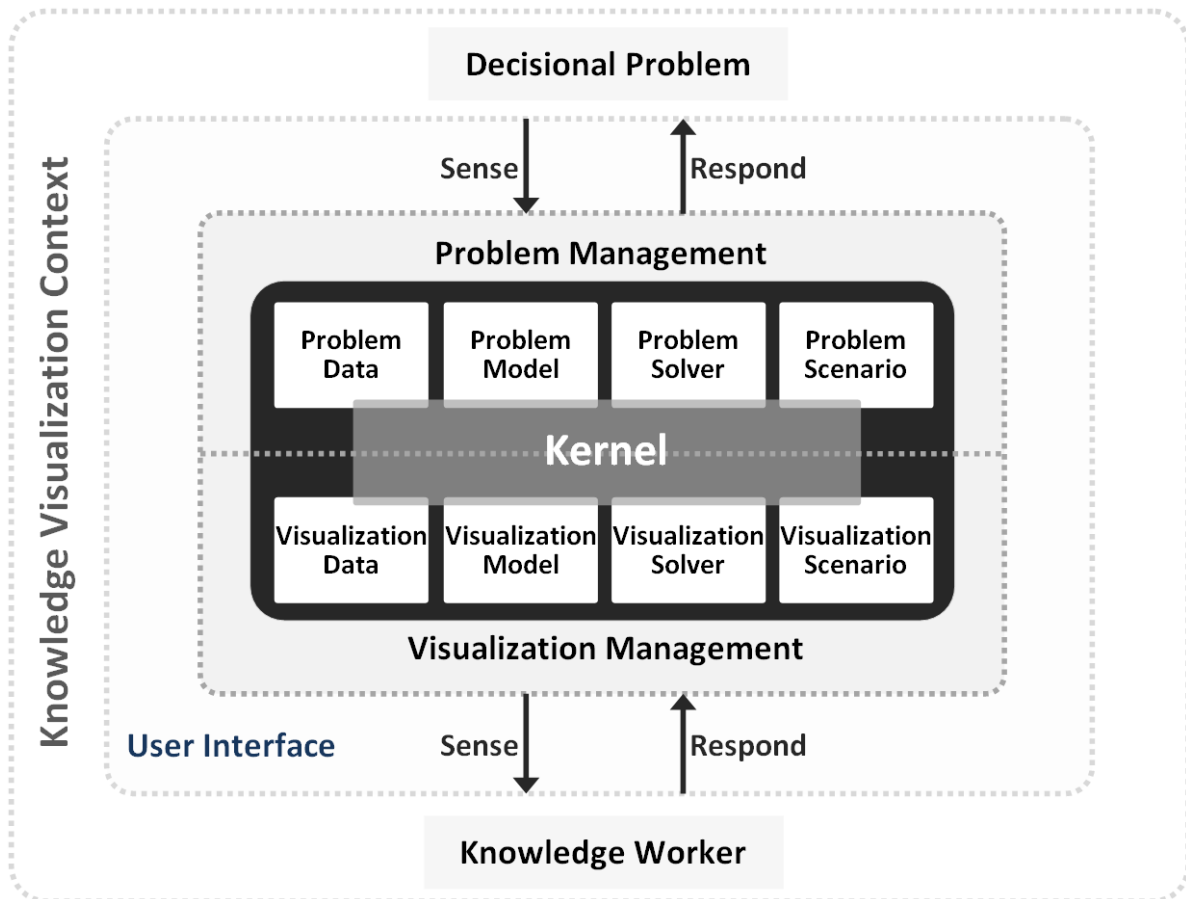


Figure 4: Contextual adaptive visualization environment framework

5. Implementation

To validate the concepts, models and framework of CAVE, we implemented a vertical prototypical system against the CAVE framework through utilizing a set of Microsoft technologies, i.e. Bing map, windows presentation foundation, ADO.NET entity framework, and SQL Server. The prototype enables the sensing of contextual changes through accessing a number of historical and/or real-time

data streams. Apart from monitoring and communicating with these data streams, the system also supports the creation of problem and visualization scenarios that enable a knowledge worker to sense and become aware of emerging situations. The impact from the contextual changes is reflected by the adjustment of visualization requirements. The prototype helps the knowledge worker to respond to the contextual changes through refining or re-creating knowledge visualization solutions, for example, mapping the problem scenario to a more appropriate visualization scenario to better fit in the new knowledge visualization context.

To help with demonstrating the support of the prototype, we introduce two cases, that is, Napoleon's army march to Russia, and child statistics. The former case resides more in the domain of historical data management while the latter is mainly about statistical data analysis. In the Napoleon's march case, we focus on exploring the relationships between army size reduction and its potential causing factors such as temperature, speed, location altitude, enemy size and available resources at each location, etc. In the child statistics case, we concentrate on discovering patterns that exist among a variety of education related indicators in different countries, e.g. primary school completion rate, expenditure per student, and literacy rate of adult. Both cases require visualizing spatial temporal multi-dimensional data. The following two sub-sections illustrate the support of the CAVE prototype at both macro level where the problem situation changes from the Napoleon's march case to the child statistics case and micro level where different knowledge workers expose different visualization preferences.

5.1 Macro level contextual change

When the problem situation changes from one case to another, the CAVE prototype allows knowledge workers to create different problem and visualization scenarios for different cases. For visualizing the invasion and retreat related information of Napoleon's main troop, in 1869 Charles Joseph Minard published a map to portray the defeat of Napoleon's army in Russia (Tufte, 1997). Building on top of the Minard's work, we created an integrated problem-visualization scenario (Figure 5) to illustrate how the army size (indicated by the width of the route band) diminishes as the temperature and moving speed change vary along the route in an animated fashion (Figure 6). In contrast, the problem-visualization scenario (Figure 7) we created for the child statistics case presents the trends of multiple education indicators in a static way (Figure 8).

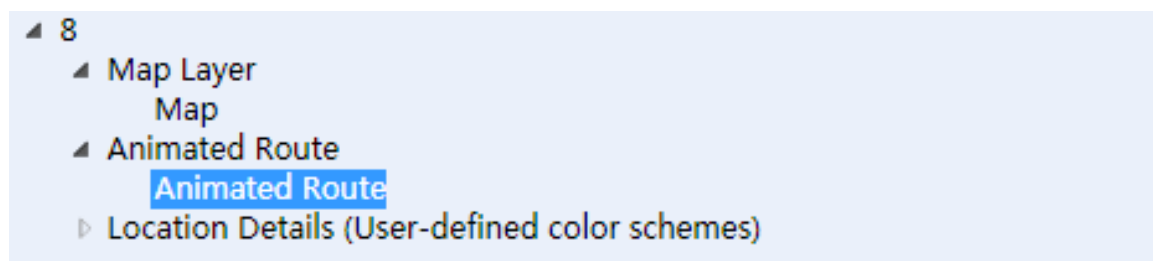


Figure 5: An integrated problem-visualization scenario for Napoleon's march case

5.2 Micro level contextual change

Knowledge sharing among different knowledge workers can require the system to accommodate their diverse visualization requirements and preferences. For example, some knowledge workers may prefer to use colour to present a high level overview of the child/education indicators to help with their comprehension of the knowledge. In contrast, others may like to watch and/or listen to the related media bites of the child/education indicators through vivid video/audio files. An example of a three-layer integrated problem-visualization scenario is demonstrated through Figures 9-11.

Figure 9 shows four indicators for each country, i.e. female children out of primary school, male children out of primary school, literacy rate of female adults, and literacy rate of male adults. These indicators are represented by the following colours, i.e. red, green, blue, and yellow, in respective. For each indicator, deeper colours indicate higher values and lighter colours mean lower values. By zooming into a detailed level, the information about how the four indicators vary across consecutive years in different countries is presented in line graphs in Figure 10. The comparison among indicators enables knowledge workers to roughly infer whether a certain relationship among multiple indicators may exist. By zooming into a more detailed level, the users may play available videos and/or audios

associated with an indicator in a particular country so as to obtain rich contextual information (Figure 11).

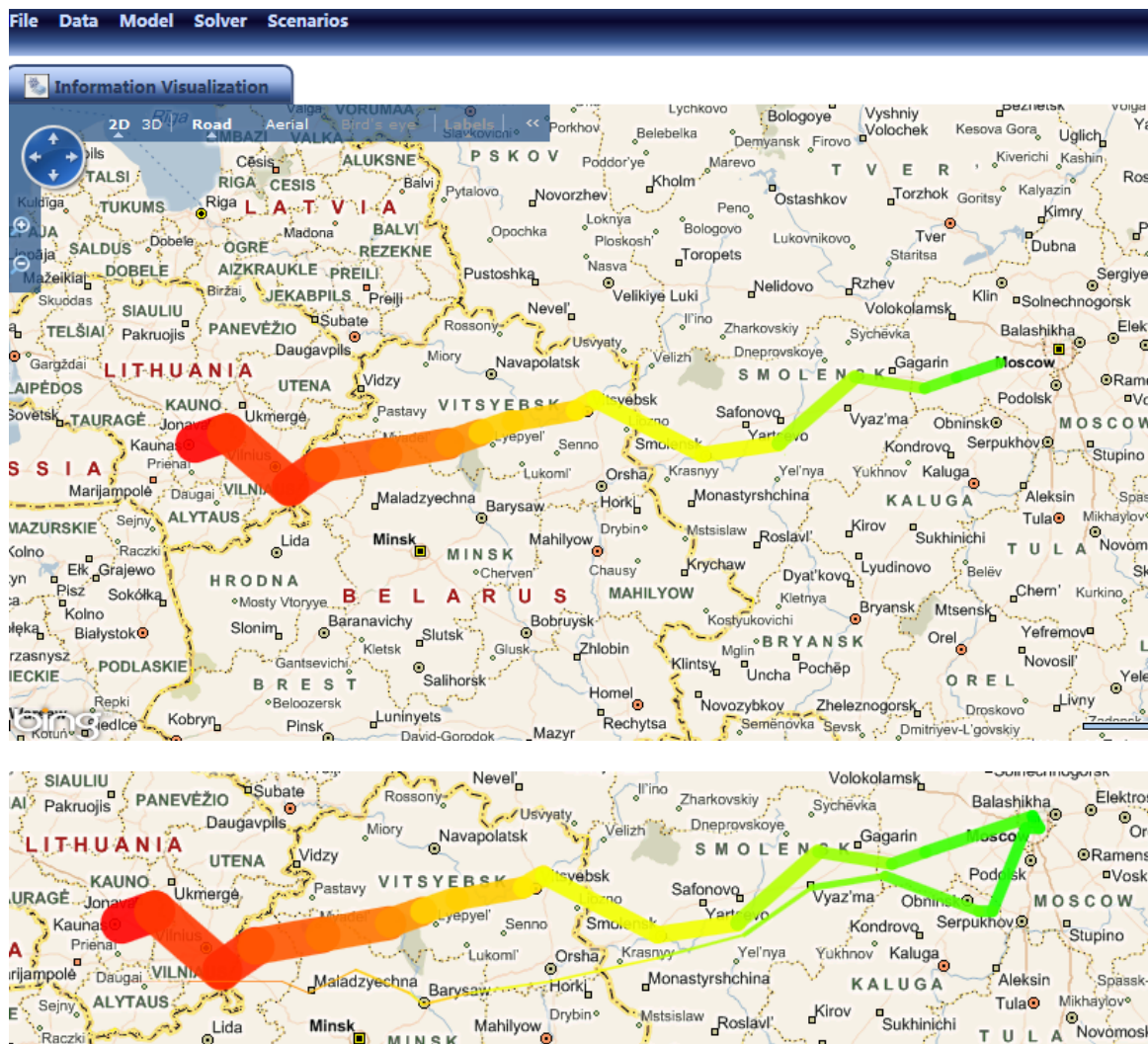


Figure 6: An animated visualization for exploring causes for Napoleon's army death

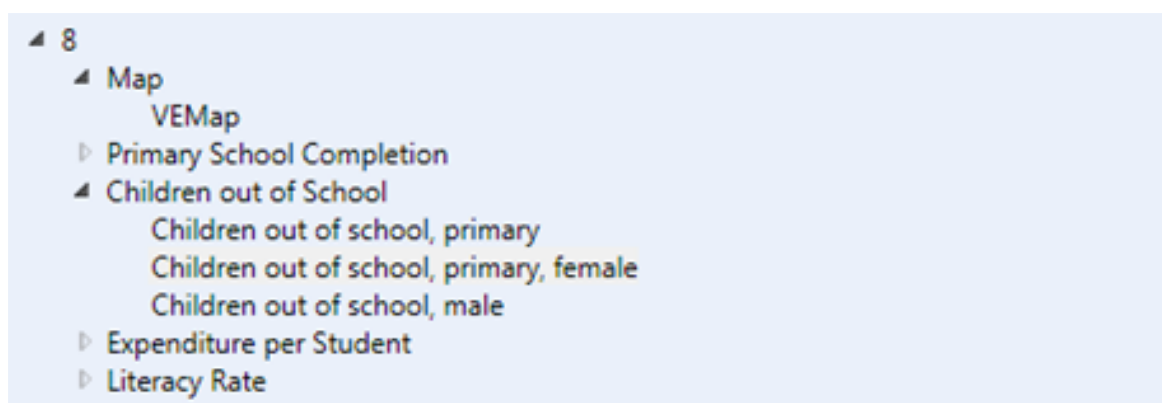


Figure 7: An integrated problem-visualization scenario for child statistics case

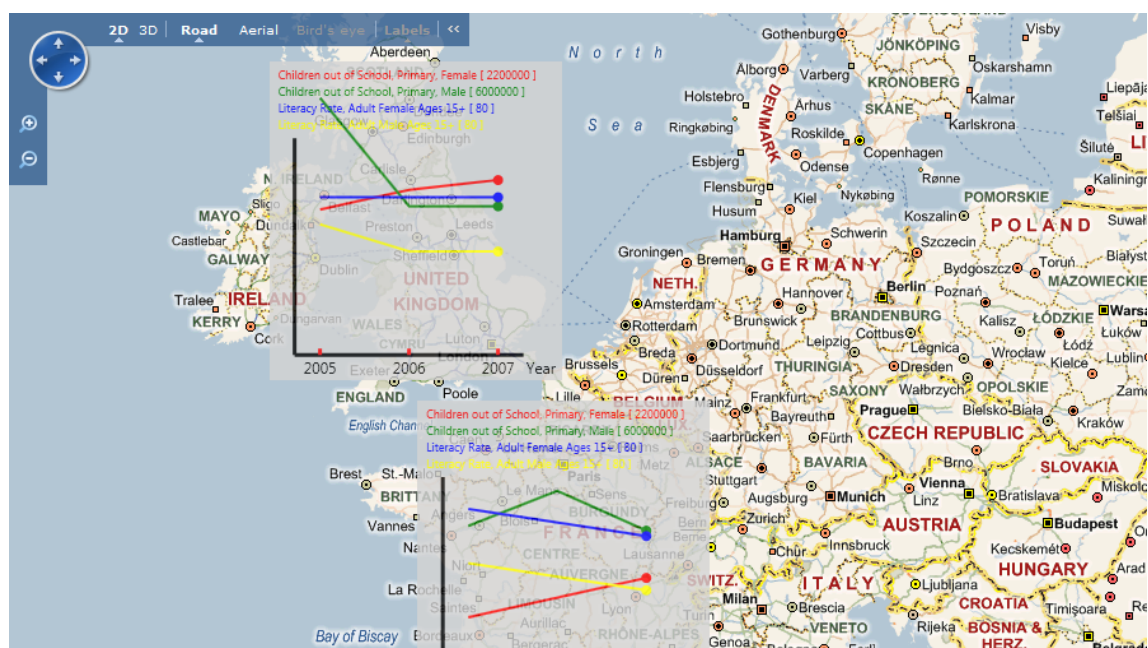


Figure 8: A static visualization for aiding the pattern discovery of child statistical data



Figure 9: Top layer - child related indicators by colours

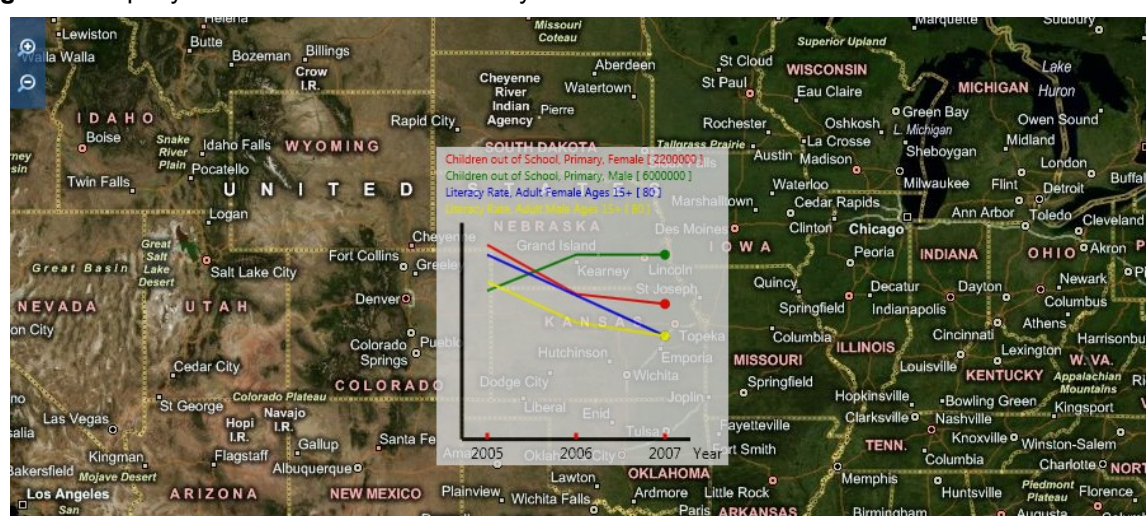


Figure 10: Middle layer - showing trends of multiple Indicators by line graphs



Figure 11: Bottom layer - presenting rich Information by videos and audios

6. Conclusion

Visualisations are integral for the creation, transfer and sharing of knowledge. Knowledge visualization context is complex and dynamic in nature. Such complexity is caused by the extensive diverse and changing factors involved in the problem, purpose and stakeholder contexts. The dynamic and changing problem, purpose and knowledge worker contexts often lead to changing visualization requirements that are ill supported by the visualizations systems involved in knowledge management. One major challenge brought by the context complexity is how to enable knowledge workers to flexibly adapt knowledge visualizations to the changing and evolving knowledge visualization context and maintain their effectiveness over time and space. To help with addressing contextual dynamics and complexity, we delineated knowledge visualization context and proposed the concept of a contextual adaptive visualization environment. The ideas involved in CAVE were further explicated through CAVE models and framework. These proposed artefacts are validated through the implementation of CAVE. The CAVE prototype is demonstrated through how it supports contextual changes at both macro and micro levels. It deserves to be that the current prototype has only been tested against a limited number of knowledge visualization context changes. Identifying and categorizing representative contextual changes as well as exploring and improving the support offered by the CAVE prototype will be accomplished in our future research.

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