

An XML-Based Infrastructure to Enhance Geographic Visual Analytics

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We propose a new streamlined two-step geographic visual analytics (GVA) workflow for efficient data storage and access based on a native web-enabled XML database called TreeTank coupled with a Scalable Vector Graphics (SVG) graphical user interface for visualization. On the one hand this new storage framework promises better scalability with rapidly growing datasets available on the Internet. On the other hand, it reduces data access and update delays for collaborative GVA environments, while improving interactivity and flexibility from an end-user perspective. The proposed framework relies on a REST-based web interface providing scalable, and spatio-temporal read-write access to complex spatio-temporal datasets of structured, semi-structured, or unstructured data. The clean separation of client and server at the HTTP web layer assures back-wards compatibility and better extensibility. We discuss the proposed framework and apply it on a prototype implementation employing world debt data. The excellent compression ratio of SVG as well as its fast delivery to end users suggests encouraging further steps towards dynamic, highly interactive, and collaborative geovisual analytics environments.

KEYWORDS: Geographic visual analytics, data storage and access, interoperability, Web interface, XML, SVG

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Introduction

GVA is a highly interdisciplinary research field, with tight links to different related disciplines, having needs and interests in

synthesizing information and deriving insights from massive, dynamic, ambiguous, and often heterogeneous data sources (Keim et al. 2006). The scientific objective of GVA is to understand how both individuals and teams carry out analytical reasoning and decision-making tasks based on complex information, and to use this understanding to develop and assess information and communication technologies for this purpose (MacEachren et al. 2006).

Increasing sizes and complexities of data sets being collected, handled and analyzed by visual analytics experts call for new cross-disciplinary approaches {Andrienko, 2008 #53}. For example, efficient and effective storage and exchange of very large and complex distributed spatio-temporal databases is not only an important enabler for GVA, but also a research focus of the database research community within computer science. While previously large geographic datasets were typically of structured alpha-numerical nature (i.e., remote sensing images, census datasets, etc.) more recently GVA researchers face a multivariate mix of structured (relational) databases, and increasingly semi-structured (e.g., XML-based), and unstructured

(e.g., plain text) data sets, all readily available on the Internet.

A flexible and dynamic data storage and access infrastructure is especially needed when representing movement, dynamism, and change (Andrienko et al. 2008). Ideally, GVAnalysts should have efficient tools at hand for interactively access, rapidly modify, exchange in real-time, or generate entirely new representations on the fly from underlying massive data sets, whenever the research context requires it.

Today, GVA user interfaces establish the necessary linkages between collected geographic datasets, data representations stored in databases, as well as external (graphic) visualizations presented to a user that interact with internal (mental) representations. Ongoing technological developments provide continuously changing data types (i.e., from tracking devices, LBS, sensor networks, audio, etc.), which in turn require new data handling structures for efficient GVA.

According to MacEachren and Kraak (2001), one of the challenges is to develop extensible methods and tools that enable the understanding of, and insights from, increasingly large and complex volumes of geospatial data that are becoming readily available these days. Scalability of GVA solutions have become one of the bottlenecks to deal with massive databases.

Many different (server-side, client-side, hybrid) data handling approaches are already available for Internet-based geographic information systems (GIS) with the goal to improve data access performance (Chang and Park 2006). Each approach has its specific advantages and disadvantages with respect to data manipulation and management, user interactivity, and the distribution of server-side or client-side tasks (Chang and Park 2006, Yao, and Zou 2008). In addition, scalability and the provision for distributed collaboration also varies significantly with each approach.

One of the main challenges for highly interactive and distributed GVA is the inherent potential for media breaks when dealing with distributed and diverse databases, thus reducing the potential for knowledge discovery. For example, knowledge might be disseminated through one media channel such as written communication in the form of emails or a journal article that summarize insights from a database that is not directly accessible anymore from this

particular media channel. Essentially, the media break is enforced by the underlying data infrastructure, as this infrastructure does not natively support the dynamic adaptation of large-scale data sets to various media channels. Each media break within a collaborative research context hinders knowledge discovery as it requires the (manual) conversion of data from one format to the next. The preparation, conversion, and reviewing steps all require time and significant computational resources when dealing with massive datasets. Consequently, real-time or interactive collaborations over a network are severely hindered.

This contribution specifically presents a data storage and a visual access framework capable of dealing with both large-scale and frequently changing semi-structured (XML-based) spatio-temporal data sets increasingly used in current GVA research contexts. The proposed GVA infrastructure enables analysts to access and modify large and complex data sets and rapidly display these changes in response to user actions, as needed for efficient and collaborative visual data exploration environments {Andrienko, 2008 #53}.

Specifically, we propose an XML-based infrastructure to reduce the potential number of media breaks within geographic visual analytics. Our infrastructure provides sound support to securely store and quickly access dynamically changing data, representing cognitive adequate knowledge in a scalable, web-based, and collaboration-oriented way. We describe the underlying technology and provide a case study to demonstrate the benefits resulting from it.

The rest of this article is organised as follows: Section 2 outlines the technological research context and related work. Section 3 describes the proposed GVA data storage and access infrastructure, followed by Section 4 where we apply the implemented prototype to a case study. Section 5 discusses our research findings, highlighting opportunities and challenges of the proposed approach. This is followed by a concluding section 6, which includes an outlook to future work.

Background

Recent developments foster the integration of data storage and display technologies in ways not possible before. The (well-designed) web-enabled geovisualization display has become an

interface to massive complex and distributed databases that can support efficient information access and knowledge construction.

The Open GIS Consortium has initiated Web mapping interoperability initiatives and specifications to develop interface specifications for geographic data (OGC 2002). This includes the Geography Markup Language (GML) encoding standard to express geographic features (OGC 2007), or the Web Feature Service (WFS) Implementation Specification for retrieving geographic features across the web (OGC 2005). In addition, geographic features stored in this fashion can be displayed using the Scalable Vector Graphics (SVG) format, an open standard developed by the World Wide Web Consortium (W3C) (Peng, and Zhang 2004). SVG is based on the eXtended Markup Language (XML) to describe two-dimensional geometric objects (points, lines, and polygons). In Neumann, and Winter (2001)'s words XML is seen as the future core-technology for all up coming web-standards.

Peng and Zhang (2004) have outlined the role of GML, SVG, and WFS in building an internet geographic information system (GIS). Open issues were in their opinion the compression of GML and SVG files, seen also as one of the easiest issues to solve. A more complex open issue is the client-side SVG user interface, and respective data processing tools to assist users as they interact with GML data. More recently, Yao and Zou (2008) have highlighted interoperability challenges of Internet mapping tools based on the open source approach. A core challenge is the efficient transfer of data between relational and object-oriented databases. For example, widely used proprietary databases such as ESRI ArcSDE or Oracle Spatial store geospatial information in a binary long data type in an unpublished format. To access this data for display with SVG first an SQL query is required. The traditional approach is to deliver the requested data in a Standard Open Format, e.g., an ESRI Generate File. An intermediate data conversion step is then required to generate the SVG document from the ESRI Generate File, before it can be presented to the user in form of an easy-to-use graphical interface (Dunfey et al. 2006).

According to Neumann and Winter (2001) databases are easier to query or update while XML is perfect for data-exchange and archiving.

SVG displays can be constructed directly out of (XML) database and be presented to a user for interactive geovisualization and visual analytical

knowledge construction. SVG is optimized for graphic rendering on the Web. Features such as, vector display, animation, interactivity, transparency, graphic filter effects, including shadows, lighting effects, and easy editing are provided with SVG (Yao, and Zou 2008). However while SVG is very suitable for graphic content delivery by providing flexibility for user interactions (Neumann, and Winter 2001), one should recognize the problem of missing topology for advanced spatial analysis, and limitations in cartographic symbolization such as missing complex line-styles.

Approach

We propose a web-enabled flexible and scalable GVA framework using a native XML-based data storage and handling back-end infrastructure coupled with Scalable Vector Graphics (SVG) at the system-user interface. This GVA infrastructure provides analysts with highly interactive, GVA tools to support complex data exploration and decision-making tasks. It includes flexible data depiction, high computer-user interaction, and collaboration over the Web.

We favor SVG for our approach, as it allows for rapid system development and prototyping, provides fast response times for interactive query requests, and supports efficient data interoperability over networks (Yao and Zou, 2008). Similarly to Yao and Zou (2008) and Dunfey et al. (2006) we expect that SVG will be supported natively in most if not all web browsers, and thus no extra plug-in will be necessary.

We natively store SVG data in an XML-based database, even though other authors have argued against using SVG as basis for geovisualization (Yao, and Zou 2008), because it is not suitable for securely and efficiently storing, managing, or delivering spatial data over the network. We argue that TreeTank solves the remaining problems such as secure and efficient storage, management, and network-based data delivery. Another XML-based language is available, the Geography Markup Language (GML), specifically targeted for geographic data. Fortunately, SVG and GML are highly compatible and can work in synergy. For example, Yao and Zou (2008) convert GML-based data to SVG before transmitting data to the client for display.

We employ the representational state transfer (REST) technology for queries to and feature extraction from our XML database. REST is a

set of network architecture principles, which outline how resources are defined and addressed. Practically speaking, REST defines a simple and scalable interface for exchanging resources over the Internet using the HTTP protocol. Each resource must be uniquely addressable through hypermedia links, meeting a universal syntax. A well-defined and typically small set of HTTP operations specifies how to proceed with the obtained resource. The basic operations are POST to create a resource, GET to read a resource, PUT to update a resource, and DELETE to remove a resource. The scalability and unquestioned expressiveness of REST makes it the interface of choice when it comes to handle large-scale SVG data on a network. The clean separation of client and server at the web layer (HTTP) allows both sides to be independently implemented while drawing from state-of-the-art standardized web technologies such as, Java, Ruby on Rails, or Adobe Flex. In addition, REST is a bidirectional interface both for querying and modifying the requested resource (Fielding, 2000).

Infrastructure

At the hearth of our contribution lies the switch to a native XML database capable to directly store and emit fine-grained XML data. Unlike traditional relational databases, native XML databases do not store the XML data as character large objects and inherently know about the XML structure and XML nodes. The finer granularity allows answering complex queries and extract the stored XML in a scalable fashion because the parsing and reconstruction process required with character large objects is omitted. In addition, most state-of-the-art native XML databases support modifications of the stored XML.

Our XML-based infrastructure consists of two components, i.e., the web interface called Temporal REST (Giannakaras and Kramis 2008), and the storage manager with the name TreeTank (code name Idefix) as described with (Gruen et al. 2006). The two components are connected to implement a two-step workflow as follows:

1. An **XQuery expression** is issued to TreeTank through Temporal REST;
2. TreeTank returns **SVG** through Temporal REST.

In stark contrast to the traditional three-step workflow based on traditional relational spatial databases, the intermediate data conversion step is eliminated, i.e., there is no need for converting the Standard Open Format such as an ESRI Generate File into SVG. The eliminated intermediate data conversion step both makes heavy use of CPU and IO and mainly contributes to the large end-to-end delay virtually inhibiting interactive Geographic Visual Analytics.

The two following sub-sections give an introductory overview over the involved technologies.

Temporal REST

While there exists a variety of solutions to access XML resources over the Web, there is – to our knowledge – no generic and unified solution to conveniently access all of:

1. The **current revision** of the XML resource or any subset thereof;
2. The **full revision history** of the XML resource or any subset thereof;
3. The **full modification history** of the XML resource or any subset thereof.

We want to work with XML as a fine-grained tree of nodes and evolve this tree over time through user modifications. As such, we realize that we can access single nodes or whole sub-trees, i.e., XML fragments, within a temporal dimension in a unified, scalable and robust way.

Only if we consider the whole life cycle of an XML resource including the past revisions and the (transaction-based) modification history, we will get a complete idea of its true power. Notably, collaboration processes frequently involve asynchronous workflows. As such, the effectiveness of the workflow largely depends on the ability to highlight the modifications, which took place during the last (or any past) step of the workflow.

We suggest Temporal REST as an interface with its related protocol message exchanges to generically implement our idea to exploit web-based XML resources. According to the Pareto principle, our proposal is simple enough for the average web application developer and at the same time it is extensible enough to be used with complex setups.

There are three different ways to access nodes and sub-trees, i.e., XML fragments, within an XML resource. First, the step-by-step tree navigation (XPath). Second, the query including joins and other complex expressions (XQuery). Third, the ID-based random node access (DOM).

Temporal REST supports all three and complements them with a temporal expression as described later. Note that XPath is a subset of XQuery.

XML IDs enable the user to tag the XML document and to quickly access the XML fragment by providing the XML ID. However, most XML nodes are not tagged with such a XML ID and are not available for random access. We suggest the tagging of at least all element nodes with a system-generated REST ID. Text nodes or attributes are accessible through their parent node. Other XML nodes such as comments or processing instructions may be tagged by the system on demand. One advantage of having the system to do the REST ID assignment is that the REST ID remains stable throughout revisions and modifications, i.e., a node or its modifications can be accessed irrespective of the revision or position in the tree. Another advantage is the guarantee of the existence of an ID. The system can make the REST IDs visible by tagging the serialized XML with REST ID attributes bound to the namespace of Temporal REST.

Each insertion operation assigns unique immutable REST IDs to all new element nodes. This assignment is made by the back-end that stores the XML and does not affect any existing user-assigned XML ID. REST IDs are numerical and they are incrementally assigned starting at one. REST IDs do not necessarily need to be assigned in document order and they must not change once assigned to a node. In addition, we suggest not reusing REST IDs. This reduces the confusion due to reassignments in future revisions. Since deletions are less frequent than insertions with most real-world workloads, the loss of number space is considered to be negligible.

Each insertion, update, or deletion of a XML node results in a modification event. Each event is assigned a new revision and a timestamp, an author, and a comment to the whole revision. Temporal REST communicates modifications by encapsulating the modified node within an item element. The item element contains the REST ID of the modified node as well as revision, time stamp, author, and comment information. As such, both the insertion and the deletion can be considered as a setting a node to a new value. Deletion sets the node to the empty node. We opted for this approach for two reasons. First, we can streamline the transport of XML fragments

and modifications within the XQuery data model, i.e., within a sequence of items. Second, the back-end can combine the storage of the modification event and the result of the modification.

The select operation allows the retrieval of a sequence of items as defined with XQuery. Each item is an atomic value, a XML node, or a modification event. The selection can be query-based or REST ID-based. Temporal REST will restrict the execution domain of both the query and the REST ID according to the temporal expression either selecting a point in time or a time period. While a query may return a sequence of multiple items, an access solely based on a REST ID will return a sequence with at most one item. If the query and REST ID approach are combined together, the query treats the node with the given REST ID as the root node of the query. The query-based approach allows to add new query languages in the future and to express complex queries including operations such as full-text search or joins. The REST ID-based approach allows to directly select an item with optimal performance since the system does not have to compile and optimize the query.

The temporal expression must be enclosed with round brackets '(' and ')' and contain a single point in time or a time period consisting of two points in time separated by a dash '-'. A point in time can be a revision number, an ISO date in short notation, i.e., without dashes or colons, or nothing, i.e., the last successfully committed revision. A single point in time will retrieve the XML fragments as they looked like at the given revision. The time period will retrieve the modifications between (and including) the two provided points in time in the according order. Leaving away the temporal expression automatically causes a fallback to the last successfully committed revision for backwards compatibility.

A single node or a whole sub-tree can be inserted either as the first child of an existing node or as its right sibling. As such, the insert operation requires a query selecting a number of nodes or a REST ID besides the actual XML fragment to insert. During the insertion process, the back-end system will assign the REST IDs as described above. Note that the insertion of an attribute must be made with the PUT operation changing the whole node.

A single node can be replaced with or without the replacement of its sub-tree. Again the updating operation requires a query to select a number of nodes to update or a REST ID. In addition, the actual updated XML fragment has to be provided. Restricting the effect of the update to the node (not effecting its sub-tree), allows the insertion of an attribute into an existing node without changing its whole sub-tree.

Whenever a node is deleted, the node and its sub-tree are purged from the system (but not from the past revisions). The deletion operation requires a query or a REST ID to select the nodes to delete.

TreeTank

TreeTank is a native XML database designed to provide scalable read and write access to XML data. TreeTank concurrently allows multiple read and a single write transaction each of which creates a new revision per transaction commit. Furthermore, TreeTank was designed to be secure and easy to maintain. The scalability of TreeTank results from the concurrent use of resources such as processing and storage units and from the design of the main internal data structure to store the XML tree.

The decision to only support a single write transaction at any time allows to run any number of processes concurrently accessing any past revisions or modifications. The newly modified data is clearly separated and only becomes visible after the last successful transactional commit to processes different from the write transaction process. If multiple users want to work on the same XML tree at the same time, either a transaction manager is required which coordinates, i.e., sequentializes the changes, or a workflow has to be established which clearly states when which user is allowed to do what. Alternatively, a locking scheme has to be established, which follows an optimistic or pessimistic locking policy. However, it turns out, that in many real-world use cases, only a single user is working on a given part of the tree at any time, or that the natural workflow of a team working with XML data resolves modification conflicts before they even could appear.

The data structure of TreeTank was optimized for updates. At most three directly related nodes must be updated, whenever a single node or sub-tree is modified. Only the modified nodes are

stored on disk in a compressed page. Note that traditional databases usually store the whole page potentially containing dozens of nodes even though only a single node may have changed. Still, care has to be taken that reads do not have to collect a huge number of scattered changes to reconstruct a single page. We opt to intermittently store a snapshot of the whole page to also support reads with reasonable performance. The mechanism of compressing all pages, only storing the page modifications, and of intermittently storing snapshots of the pages helps to reduce the storage requirements by one order of magnitude. TreeTank consequently does not consume significantly more space even though it can swiftly reconstruct any past state or modification.

Security is not a choice with TreeTank – it is always activated. Care was taken to only implement time-proven cryptographic primitives with sufficient key lengths and well-chosen cryptographic modes not to create a weak link, which could be attacked to break the whole system. TreeTank encrypts all compressed pages before they are stored on disk. This guarantees the confidentiality of the stored XML tree, no matter whether the TreeTank files are exposed to the public or transferred through insecure networks. Besides the encryption, a strong message authentication code is derived from each compressed page and stored with the reference to this page. As each reference contains the message authentication code of all its children, the integrity and authenticity of the whole TreeTank can be verified recursively. The root message authentication code can be securely signed and further secured by an external secure time stamping mechanism, which also assures that modifications can not be denied. The availability of TreeTank can be guaranteed on the application level by a master-slave replication, which consumes very little network bandwidth and is perfectly suited for geographically distributed operation. The master-slave setup assures that all modifications applied to the master are synchronously or asynchronously propagated to the slave. The tight integration of security allows to store sensitive data in the TreeTank. This is especially important because visualizations are usually based on large data sets collected from the internal operation of an organization or project and must not be exposed to the public.

Preliminary measurements on a state-of-the-art desktop computer show two significant advan-

tages of TreeTank. First, it compresses the original XML data while storing it in its native data structure. Second, it allows to quickly retrieve the original XML. The promising preliminary results of both the compression and time measurements for three SVG files of different sizes are as follows: The size of the TreeTank is up to ten times smaller than the original SVG file and TreeTank can deliver the original SVG data up to twenty times faster than a relational database with spatial extensions. The excellent compression ratio is due to the verbosity of SVG. The time of the data conversion step alone (excluding the time to retrieve the original data from the spatial database) takes much longer than the time required to retrieve the whole SVG from TreeTank.

Case Study

In this section, we provide a case study to demonstrate not only the feasibility but also the significant benefit a user can gain from our infrastructure. Most importantly, we want to build a mindset of how to design and use our infrastructure because it is notably different from traditional workflows both on the technical and application level. With our infrastructure at hand, the user can organize and later modify the data in the XML tree, as he likes. He can mix document-centric sub-trees containing information, e.g., in the OpenDocument format, with sub-trees compliant with ready-to-visualize SVG data, as well as data-centric statistical information.

Throughout this case study, we build up an example TreeTank essentially based on the gross external dept positions in US\$ per person. This information is available on a quarterly base and perfectly suited to show how a team can elaborate sophisticated visualizations based on a set of statistical data. Four revisions of the visualization can be seen in Figure 1. Figure 2 depicts an additional example of how GUI elements can be laid out with SVG (including a sample chart). Note that the TreeTank is exposed to authorized users through a web service running Temporal REST.

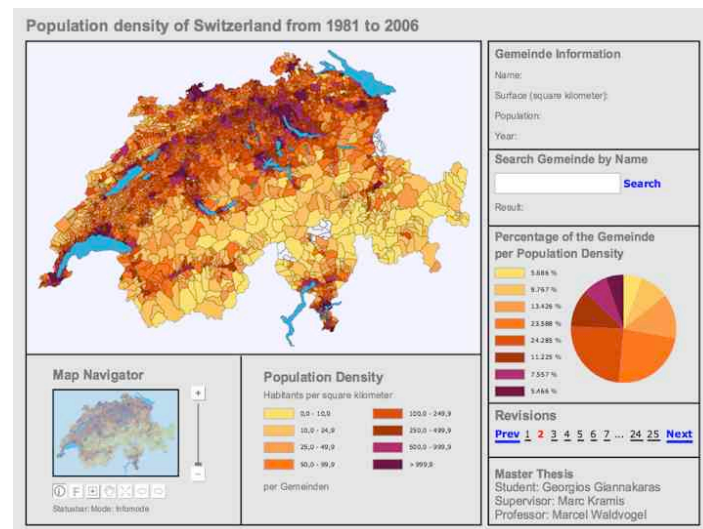
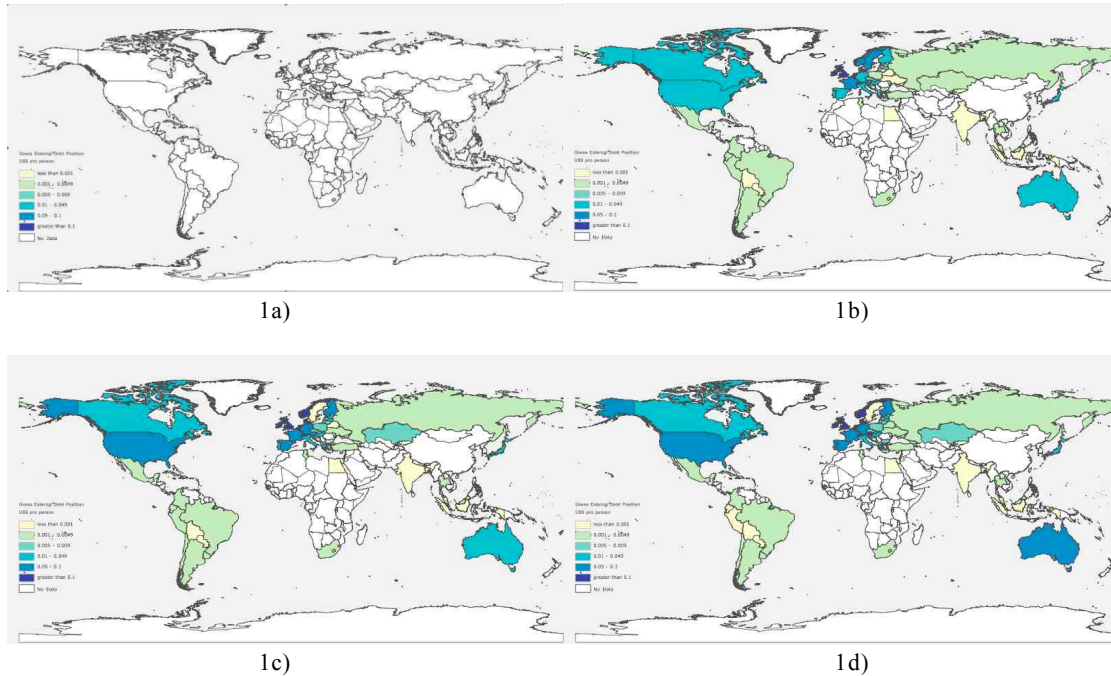
The first step is to convert the Excel-based statistical information into a data-centric XML. This is a straightforward step and only required if the original data is not available as XML. The resulting XML can be directly imported into TreeTank by inserting the whole XML docu-

ment through Temporal REST. From now on, we can query Temporal REST to extract the whole document or any sub-tree therein.

For the second step, we need a SVG representation of the world with all countries. Either, one can rely on open source SVG world maps or retrieve an individually configured world map from a traditional relational spatial database to best suit special requirements. To keep the statistical data separate from the SVG data, we insert the new node *statistic* as the parent of the statistical XML data. Then, we insert a new node *geodata* as the right sibling of *statistic* and group the two nodes *statistic* and *geodata* under the third new node *example*. We then insert the whole SVG data under the node *geodata*. From now on, we can retrieve the plain statistical data by selecting the sub-tree rooted at *statistic* or visualize the world map within any SVG-enabled web browser by selecting the sub-tree rooted at *geodata*. To combine the statistical data with the visualisation, we have to make sure that both sub-trees store the ISO country codes for each country. If this is not already the case, we can update each country in each sub-tree. Note that most SVG-based world maps will separately store a SVG path for each country.

Meanwhile, we created a set of revisions, each consisting of a Temporal REST modification request. At any time, we can retrieve an older revision or list the modifications applied to past revisions. This is convenient, if one wants to know what changed, e.g., in the sub-tree under *geodata*. It is also appealing, because one can revert the tree to a past revision if an unintended modification took place. At no time, data is overwritten or lost. Furthermore, the author of the changes can provide commit comments with each Temporal REST modification request to document his intentions and the evolution of the tree.

We prepare the visualization of statistical information by defining value ranges and color schemes for each value range. Then, we add the color information as an XML attribute to each element in the *statistic* sub-tree based on the statistical value and make sure that the statistical information is grouped in sub-trees for each year, and within the years for each quarter. Next, we add the SVG elements to the *geodata* sub-tree required to draw a box displaying the color scheme and value ranges. To better support layering in SVG, we group the SVG elements required to draw the box under the XML element



description and then group the SVG path elements required to draw the world map under the XML element *worldmap*. This step helps to interactively enable or disable layers and can later be extended to support, e.g., layers containing waterbodies, charts, or other GUI elements

required for improved and convenient user interaction. To prepare the coloring of the countries according to the selected statistical data, we add the appropriate SVG color attribute to each path element. Finally, we add a SVG

GUI element under *geodata*, which allows to interactively select a quarter of the year.

The actual procedure to color the world map according to the selection can either be implemented with an XQuery expression issued through Temporal REST or with JavaScript on the client side. If XQuery is chosen, one must select both the *statistic* and the *geodata* sub-tree and then set the color attribute of the SVG path elements to the color attribute of the statistical data by joining them by country code. When JavaScript is preferred, both the *geodata* and the sub-tree containing the statistical information for the selected quarter have to be transferred to the client and then joined together by looping through all countries and setting their color to the color value found in the statistical data. Note that the statistical data can be reloaded efficiently and on demand with Ajax technology. The main difference between the XQuery and the JavaScript variant is, whether the work is done on the client or the server side, and how much data has to be transferred over the network. In the case of XQuery, the join is calculated on the server side for each request. Then, the result is transferred to the client and immediately visualized. In case of JavaScript, more data has to be transferred to the client for the first request. Then, the join is calculated and visualized. For later requests, only the new statistical data is transferred, joined and visualized. Consequently, JavaScript is the better choice, if the workload consists of multiple selections for different quarters. However, note that current JavaScript runtime environments are so slow that the XQuery variant might be faster even though the whole data for the visualization has to be transferred for each request. This may change in the near future since most JavaScript runtime environments currently undergo major rewrites to speed them up significantly.

We have shown that the XML tree can be grown exactly according to the user's demand. All involved data sources can gradually be integrated with TreeTank and then queried and further modified from within one single infrastructure. While the last paragraphs only considered a single user performing the modifications, we describe the collaboration of multiple users collectively working on the same TreeTank in the next paragraphs. Note that each user can modify the XML tree and add more statistical data or visualization elements as described before. Though, it is important – as in any professional publication or authoring workflow –

that each user behaves according to a policy. With TreeTank and Temporal REST, it is a simple one:

Concurrent modifications have to be done in disjoint sub-trees.

While the current version of TreeTank does not provide a facility to enforce this behavior, it can be implemented technically on the application layer or non-technically in the organizational structure. We suggest a hierarchical responsibility delegation scheme:

At any time, one author (person or process) is responsible for a given sub-tree unless he delegates a descendant to someone else with the option to revoke.

This scheme can be extended by a non-hierarchical access-control-list-based (ACL-based) scheme if required. To clarify the hierarchical responsibility delegation scheme, we imagine a situation where one author A1 adds more statistical data each quarter, one author A2 works on the SVG-based GUI and color schemes (Brewer 1994), and one author A3 links the visualisations to scatter plots or other statistical graphics (Andrienko and Andrienko 1999). One possible hierarchical delegation then is as follows. The owner of the TreeTank delegates *statistics* to A1 and *geodata* to A2. A2 creates a new node *charts* and delegates it to A3. Then, all three authors concurrently modify the tree and will never cause isolation conflicts such as lost writes or dirty reads as they are stated in the ACID model, which is one of the oldest and most important concepts of database theory. Lost writes are prohibited by design because each author works in his responsibility domain, i.e., a dedicated sub-tree. Dirty reads are avoided because each author will only see successfully committed changes and has the option to query the tree as it was like at a fixed revision. Whenever he wants to switch to a newer revision, he first checks for modifications on the sub-trees of interest and whether they impact his own work, e.g., introduce an inconsistency because the color attributes were dropped. Finally he can adapt his part of the tree to the modifications.

Discussion

The findings from the case study based on a prototype implementation of our XML-based infrastructure open a wealth of opportunities for the end-user as well as an array of research

challenges. The immediate benefit of our infrastructure is the very efficient use of processing and storage resources. Much more user requests can be handled per time unit and the degree of interactivity is dramatically improved, as the user actions are no longer a matter of minutes but seconds. Both throughput and interactivity are essential for collaboration-oriented environments where end-users are used to interact in an asynchronous as well as a synchronous fashion. The support for the evolutionary growth of tree (XML) data structures and the ability to store and query, e.g., statistical and SVG data, side-by-side, help to reduce unnecessary media breaks, which hinder the dissemination of (visually) discovered knowledge.

The research challenges are manifold. One challenge is to find and categorize tree structure and tree design patterns. Our infrastructure allows to store huge amounts of unstructured data in a single TreeTank. Without patterns, the TreeTank is likely to end up as a junk room where everything is contained but rarely something can be found in time. Hand in hand with the patterns comes the question how to best organize and manage the concurrent access of multiple users assuming changing roles. In our case study, we suggested an organization form natural for tree-based data structures. But there may be other more efficient ones. As with the tree structure and tree design patterns, the collaboration-oriented (authoring) workflows have to be collected, categorized, implemented, and tested with real teams. From a technical point of view, the challenge arises to integrate various indices with TreeTank to speed up specialized queries such as full text queries or spatial queries on rasterized data. While the server side can be further sped up with the help of indices, the client side GUI and JavaScript environments still need to be revised to unleash the processing power of modern desktop or notebook computers. The GUI functionality of browsers and SVG plug-ins is not yet on par with native applications. Even the extensive use of Ajax and JavaScript does not hide the current shortcomings.

The case study made the assumption that there are multiple users but only one single TreeTank. In case that multiple teams concurrently grow their data structures in independent TreeTanks, the question arises, how all these distributed TreeTanks can be integrated into one unified storage. While our infrastructure solves the

aspect of integrating different data sets into one tree, it does not yet provide support to integrate multiple trees into a forest.

Conclusion

We propose a new streamlined two-step GVA workflow for efficient data storage and access based on our native web-enabled XML database TreeTank and couple it with a SVG graphical user interface for visualization. Not only does our XML-based infrastructure substantially reduce access delays due to the elimination of intermediary data format conversion steps. It rather extends the user's options by providing significantly better scalability, inherent data security, and, most importantly, the ability to collaboratively work in GVA environments thanks to optimized update support. With up to twenty times shorter data access delays and up to one tenth of the traditional storage requirements, our infrastructure aims at improving interactivity and flexibility from an end-user perspective.

Furthermore, our infrastructure suggests a paradigm shift leaving behind dispersed disconnected data sets as well as media breaks and introduces a tightly integrated unified storage for complex spatio-temporal datasets of structured, semi-structured, or unstructured data. The clean separation of client and server at the HTTP web layer assures back-wards compatibility and better extensibility. Future work is going to fully implement the latest XML query facilities such as XQuery, XQuery Update and XQuery Full Text to give the end-user state-of-the-art tools at his hands to query large-scale data sets. Especially the full-text feature will further improve the value of our infrastructure for the collaboration-oriented end-user because he can freely search in all comments and documents stored along with the spatio-temporal data. Besides this, we will investigate, how to most efficiently distribute TreeTank for even better scalability.

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