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Mapping the Fourth Dimension: the TimeMap Project

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Abstract

This paper outlines the need for an explicit methodology for recording and managing spatio-temporal data in archaeology and related disciplines. It describes the essential components of a methodology being developed by the University of Sydney TimeMap™ project, viz: a model for recording spatio-temporal data; provision for recording fuzziness in spatial and temporal limits; temporal interpolation between known information; display and animation of data through a time-enabled GIS interface; and a metadata standard allowing access to remote datasets across the Internet without restructuring. Examples of the user interface and animation products are included.

For more information on the TimeMap project visit the TimeMap website

1 Introduction

1.1 Overview

Whatever one's philosophical views on the nature of the Universe, for most practical purposes human beings exist within a three-dimensional space moving inexorably through time. Archaeology, as a discipline intimately concerned with human beings, time and space, has paid remarkably little attention to the difficult issue of effectively recording and presenting the products of human activity in a spatio-temporal context. Our methods of time description in particular have their roots firmly in 19th century natural sciences and mid-20th century scientific method.

In this paper I will outline some of the issues in recording and visualising the time-space context of archaeological and historical records, and describe the University of Sydney TimeMap project[1]. This project aims to develop a methodology and software for recording, visualising and, eventually, analysing features which evolve through time (see Fig. 1), such as the spread and decline of empires, patterning of settlements on landscapes, landscape change, urban growth, demographic data or the progress of military campaigns.

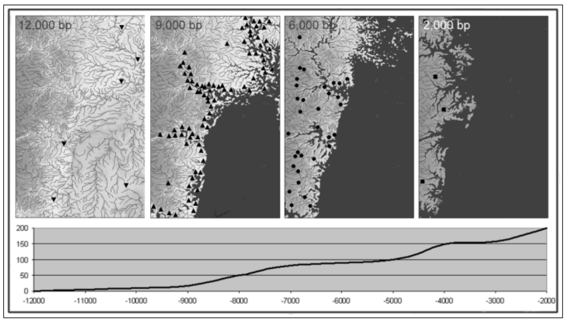


Figure 1. Examples of time-dependant features.

1.2 Antecedents and current work

1.2.1 The time dimension

Conventional GIS are essentially two-dimensional. Even those that describe themselves as "virtual" or three-dimensional GIS are 2D programs with routines for handling a special attribute, z, of each x,y position in their feature-space – they do not treat z on an equal basis with x and y[1]. Currently available commercial GIS packages make no special provision for time (t) as a fourth dimension.

To provide a comprehensive solution to the storage and analysis of spatio-temporal data, one needs to explicitly handle time on an equal basis with x and y providing, for example, a continuous feature-space and topological capability in x, y and t. This might be regarded as the Holy Grail of temporal GIS (TGIS). It is not necessarily the solution to our particular needs when dealing with archaeological or historical features, as I will discuss later.

1.2.2 Temporal GIS

In chapter 2 of her seminal reference on temporal GIS, Langran reviews the literature on spatio-temporality and comes to the conclusion that "… while researchers have not neglected spatiotemporal issues, the work that exists suggests only a bare sketch of a temporal GIS" (Langran 1992, 24). Interestingly, this book was supported through a fellowship from Intergraph Corporation, one of the main players in the commercial GIS sphere, but there is no obvious sign that the company has pursued the ideas developed, at least not to the point of commercialisation.

It is apparent that, although temporal GIS is often cited as one of the cutting edges of GIS research, and there are certainly a smattering of relevant papers at GIS conferences, the same names seem to appear repeatedly. Some attempts have been made to develop TGIS using existing GIS tools, for example thesis work by Jonathan Candy (Candy 1995) who wrote a TGIS in Arc/Info macro language (AML). One of the few active research projects working on the development of a general-purpose analytical TGIS from scratch is the Tempest project at Pennsylvania State University (Peuquet and Wenz 1994). The authors of this project are only aware of a small number of researchers in this field and believe that the need to completely rethink GIS, rather than modifying existing software, has discouraged those who have dabbled in the area (Peuquet, pers. comm.). Interestingly, the first test case they used was an archaeological site.

1.2.3 Time-enabled 3D modelling

The main thrust towards geographical display of time-enabled databases seems to have occurred as a natural progression from architectural and urban planning 3D visualisation work. In this field, several groups are implementing or planning ambitious systems. Perhaps the most ambitious is *Rome Reborn*, a project which aims to use a VR simulation system called uSim, developed by the UCLA Department of Architecture and Urban Design (http://www.aud.ucla.edu/bill/uSim.html), to simulate Rome from the 9th to 4th centuries BC. The planned completion date for the project is 2020, although a simulation of a limited area is planned for completion by the end of the millenium.

The Center for Landscape Research at the University of Toronto (http://www.clr.utoronto.ca:1080/) has developed an object-based time-aware database and visualisation toolkit called PolyTrim (Hoinkes and Lange 1995; Hoinkes and Mitchell 1994) which has been used to create a time-enabled visualisation database for historic Montreal, among other projects. Their model-viewing software has different interfaces for research use and public access, but is unfortunately limited to SGI workstations (it is available for download from ftp://ftp.clr.toronto.edu/pub/sgi/clrview). There are numerous other projects in the planning or pilot study stages, such as the Metro Denver Temporal GIS project (http://www.csn.net/~castagne/ - includes useful links to other projects).

1.2.4 Time series and urban growth

One area where temporal considerations have long been specifically recognised is in satellite remote sensing, where the use of a time series of coincident scenes may be used to identify the evolution of a phenomenon (*e.g.* floods, bushfires, crop growth, deforestation or urban expansion) or as a means of identifying vegetation through its seasonal response. The US Geological Survey EROS Data Centre’s Temporal Urban Mapping project (http://geo.arc.nasa.gov/umap/umap.html) aims to visualise the growth of US urban centres, notably the Washington-Baltimore area and San Francisco Bay areas. NASA-Ames Research Centre and Hunter College are co-operating on a project, funded by the USGS Global Change Research Program, to model the growth of the San Francisco Bay area (http://geo.arc.nasa.gov/usgs/clarke/hilt.html). The data for these visualisations is partly historical (for the earlier parts of the sequence) and partly derived from analysis of satellite imagery (for more recent times).

1.2.5 Archaeological and historical applications

Over the last few years there have been increasing numbers of papers which apply some form of GIS-based spatio-temporal mapping to archaeological and historic data or landscape data of archaeological relevance. For example, Snow (1997) uses a sequence of maps generated with MapInfo to create an animation of Iroquois settlement from AD 750 to the present; Spikins (1997) presents a sequence of reconstructed vegetation maps for the Holocene and discusses their significance for population change; Nuñez *et al.* (1997) animate the changing configuration of the landscape due to post-glacial sea-level and isostatic effects.

Museums are increasingly using animations to present information as part of exhibits, particularly in the presentation of changing landscape configurations or historical information in a geographical context. There are a growing number of animations and VRML models appearing on the WWW, for example those produced by the Illinois State Museum GIS Lab (http://www.museum.state.il.us/research/GISlab).
In the commercial sphere, electronic encyclopaedias are beginning to use animated cartographic representations of history; Grolier’s encyclopaedia introduced such maps in their 1994 edition, and used them as part of their sales pitch to seek a competitive edge over the competition (DiBiase 1994). These animations are time-intensive (200 hours per 5 minute animation) one-off productions which use GIS for creation of some elements, but assemble the animation in a multimedia authoring package. Other CDs use time-series maps as a navigation metaphor for viewing historical data *e.g. Angkor, cité royale* (Infogrames Multimédia 1996).

In almost every case, the application is intended as a one-off production or case-study rather than a general methodology (which does not of course preclude their application to other similar situations) and the final product is a simple animation of individually-generated time-slice maps, or an animation built from separate components in a multimedia authoring environment. Nothing I have seen so far allows the interactive control and querying of a GIS-based temporal database and interactive generation of animations from the database. This is the main aim of the TimeMap project.

I am sure that there is a submerged iceberg of graduate students pursuing the issues of including time in a GIS, and we will doubtless see the appearance of numerous applications in the next few years. One such project is an attempt to develop a time-enabled GIS of excavation data using ArcView (Miles Perigo, University of Nottingham. pers.comm.). Other projects may well be using time-enabled GIS to resolve specific archaeological problems without publicising the methodological aspects.

1.3 The impetus for TGIS

The impetus for temporal GIS is obvious if one considers the potential benefits it would bring to a wide range of users. Applications include the storing of histories (*e.g.* of utility networks, land ownership, climatic events, flooding, ecological indices, historical events), analysis of change (*e.g.* describing forest clearance, urban growth or greenhouse effects) and prediction of future conditions based on past history.

To date, most temporally-enabled work has been in the form of *ad hoc* solutions (*e.g.* simulations, predictive modelling, change analysis with standard GIS), or in the form of special-purpose software, (*e.g.* AFM, catchment analysis, storm & flood prediction). Such applications are legion.

1.4 TGIS and archaeology

Archaeologists have a vested interest in the development of temporal GIS, because so much of what we do is based on spatial data with an inherent temporal component. Whatever we touch (changing landscapes, changing settlement patterns, social or economic change, the development of an individual settlement, stratigraphic sequences) we are dealing with an explicit or implicit temporal component.

The crop of recent time-based maps and animations in archaeology demonstrates the need for an explicit temporal GIS; one which would generate these products and allow interaction with spatio-temporal data without problem-specific, one-off programming efforts, in much the same way as we now take simple desktop mapping or relational databases for granted. I don't think we can hope for affordable desktop solutions from the GIS industry in the next few years; I may well be wrong, but the problems of generalisation are intractable and we haven't yet seen the antecedents which might evolve into the desktop solution. It is therefore up to us to develop the subset of solutions which apply in our domain.

2 A methodology for mapping time

2.1 Essential components

What are the elements we need in a methodology for handling spatio-temporal data? I believe they can be broken down into the following distinct requirements and/or areas of research:

1. A temporally-explicit methodology for recording information about changing features and/or changes in the landscape;
2. A means of interpolating intermediate conditions between known points in time;
3. A means of recording uncertainty and diffuseness in the spatial and temporal extent of features;
4. A means of displaying information which has a fourth (temporal) component, in addition to the normal three spatial components, on a two-dimensional screen.

These issues are the central core of the TimeMap project. In addition we wish to allow data access from a variety of pre-existing data sources across a local network or the Internet, without special-case modification of either the data source or the program. We have tackled this aspect by defining a *metadata standard* (section 3.3) which interposes between the software and the data source(s).

2.2 The TimeMap Project in a nutshell

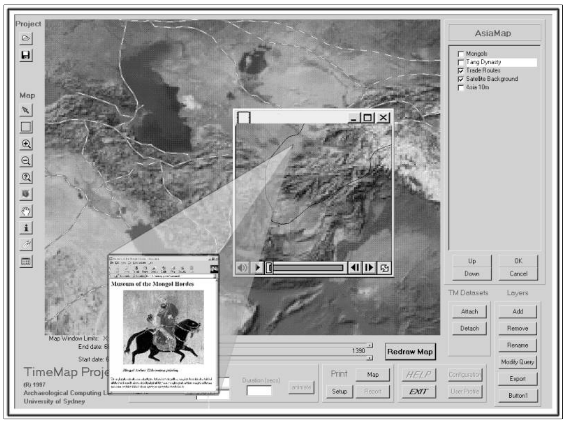


Figure 2. The prototype TimeMap display software (TMView) interface with mock-ups of animation and browser windows.

The TimeMap project aims to develop a software system (see Fig. 2), backed by an explicit spatio-temporal data recording methodology incorporating spatio-temporal fuzziness, allowing:

1. the superimposition of data layers, including base maps and satellite images, in a time-enabled GIS interface;
2. querying and display of data layers with explicit support for temporal information & spatio-temporal fuzziness;
3. derivation of data layers by query from remote datasets across the Internet without reformatting or case-by-case programming;
4. generation of data-based in-line and off-line animations and VRML worlds;
5. navigation from features on the screen to information resources on the WWW.

2.3 Modelling time-varying features

One of the first steps in our project has been to develop a model to allow the recording of spatio-temporal data. We refer to this model as the *snapshot-transition model* (see Yuan 1996 for a review of other spatio-temporal models). In this model, the history of *features*[1] is modelled as a series of *snapshots* at known points in time, and a series of *transitions* between these snapshots (see Fig. 3). Snapshots may consist of 2D vector objects (points, lines or polygons representing features on the surface of the landscape), 2D raster objects (geographically registered images, DEMs or other topographic and environmental data), or 3D models of structures.

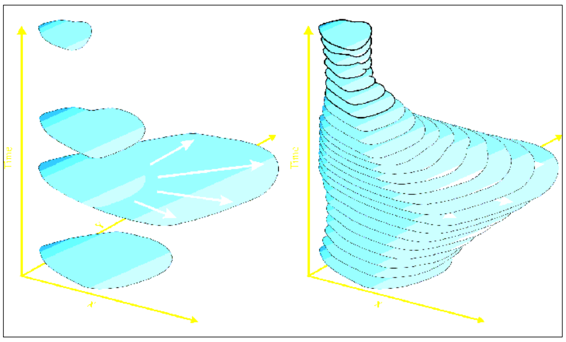


Figure 3. The snapshot-transition model of a feature (viewed in a 'space-time cube'): snapshots (left) and interpolated sequence (right).

This model is not a topological model – it does not record the spatial or temporal relationships between features, only their position in space and time (from which a topology can be inferred, as is done by non-topological GIS or desktop mapping systems). We believe this will provide an adequate base for mapping features through time, without the overheads in complexity or data processing involved in building a topological model. A similar logic has been applied by the CLR project on historic Montreal, which adopted an object-based non-topological model as "Topology-based data structures which make systems like Arc/Info so adept at the analysis of spatial relationships also make it virtually impossible to perform continuous mapping and querying in an interactive environment" (Hoinkes and Mitchell 1994).

The strength of the snapshot-transition model is that it parallels our knowledge of the past. Typically, we have fairly detailed knowledge about features at specific points in time (excavated structures and modifications are dated; they appear on a map, drawing or photograph at a given date; or they are documented in written records), but little knowledge of what lies beyond their boundaries. In between our snapshots of knowledge, in what we are terming a *transition* period, we have no specific knowledge about the feature.

However, we often have *some* idea on how one snapshot turns into another, because we know something about the processes acting on the object, or because we can reasonably assume uniform rates of change. For example, if we were considering a railway line under construction, we might reasonably assume a linear growth between the end point in 1897 and the end point in 1898, in the absence of any knowledge indicating non-uniform construction. On the other hand, if we knew that there was a major strike for several months immediately following our 1897 snapshot, we might posit a stagnation-plus-growth-spurt transition between the two snapshots.

The snapshot-transition model not only fits the nature of our knowledge of the past, but it is also relatively easy to implement, as snapshots can be recorded using conventional 2D GIS techniques[1]. We currently collect information by digitising in MapInfo and applying a range of tools (including Microsoft Access, Idrisi and one-off programming) to build the database. We hope to integrate the data-building tools as an application under Delphi towards the end of 1997.

In the process of developing the model we experimented with a number of different data structures, but ended up simplifying the model so that each snapshot is a discrete view of a feature and any knowledge about stability or changes in a feature are transition information [1]. As a result, our model can be approximated by almost any database containing records describing the same feature at different times, allowing data from a variety of sources to be integrated (section 3.3).

2.4 Temporal interpolation

Snapshots do not in general fall conveniently at the point in time for which we would like a map, nor do they offer the smoothly changing pictures we require to animate change. In order to create maps for a given date, or to create frames in a map animation series, we need to interpolate visual representations of features in the transitions between snapshots (see Fig. 4).

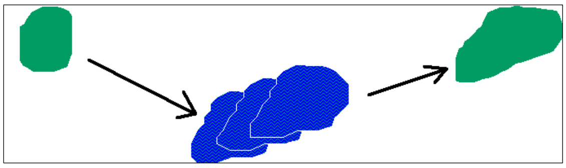
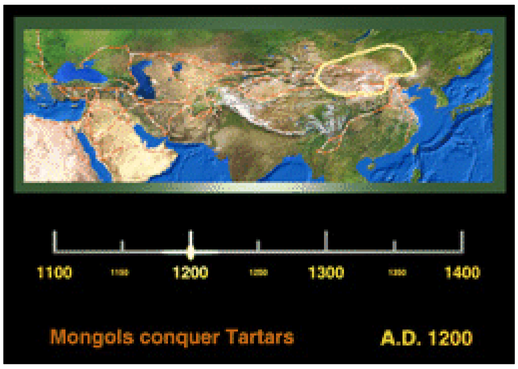


Figure 4. Interpolation of intermediate visual representations from snapshots.



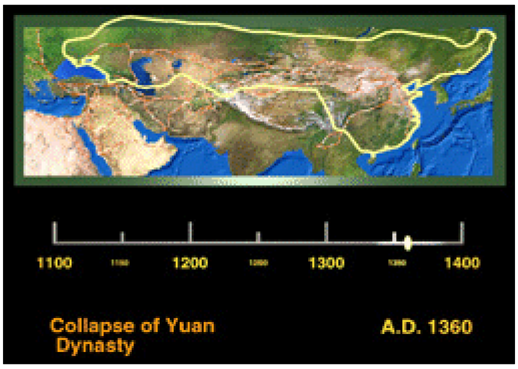


Figure 5. Stills from Mongol animation generated with Houdini.

2.4.1 Vector interpolation

In the Mongol empire animation (see Fig. 5 and animation on CD), developed by Roland Fletcher and Pat Caldon, we employed Houdini, a high-end animation package widely used in the movie industry, to create smooth transitions between successive snapshots, in this case recorded as polygons representing the extent of the Mongols at successive times. Initial attempts to morph between the polygons demonstrated three types of problem:

1. Shared boundaries of successive incarnations (snapshots) of a polygon could not always be digitised repeatably, resulting in undesirable animation artefacts along these edges;
2. Morphing between polygons required the identification of pairs of equivalent points on each polygon to guide the morph, otherwise the software had no way of knowing the trajectory of any given point from one outline to the next;
3. Thinning or addition of nodes was required where the number of points in the polygons being morphed was markedly different.

As a result, animation of the Mongols was a prolonged, labour-intensive process, requiring considerable skill on the part of the operator, and not readily reproducible if the parameters of the animation are changed. Furthermore, building-in specific knowledge about the nature of transitions - *e.g.* known campaigns of conquest - is a particularistic *ad hoc* exercise, rather than being data-driven.

Building on our experience with the Mongol animation, we have identified a number of ways of streamlining the data collection and animation process for 2D vector data. We are currently developing appropriate digitising protocols and software to permit a relatively unskilled operator to move from data collection to animation without learning the demanding skills of sophisticated animation software. Certainly the latter will produce more visually stunning results in the hands of a skilled operator, but the product comes at enormous price in terms of time, skills and lack of what-if flexibility.

2.4.2 Raster interpolation

Interpolation of raster objects is rather easier than interpolation of vector objects, as one simply needs to blend cell values from the enclosing snapshots. In doing this it may be necessary to take into account the differing cell resolutions and spatial extent of the rasters, although this can be obviated by standardisation of successive snapshots so that areal coverage, projection and grid size are the same.

Rather than interpolating between snapshots, it would be possible to define mathematical or empirical functions, possibly involving multiple GIS layers, to roll-back or roll-forward a single raster object, such as a modern vegetation map (*e.g.* by applying a model of climate change). However, it is not possible to provide for the recording and application of an open-ended set of GIS models; consequently, we feel that such predictive work should be carried out using the best tools and expertise available, and then incorporated into the data as a series of snapshots at whatever temporal frequency is required to provide adequate definition of the changing data.

2.4.3 3D model interpolation

We have not yet tackled the issue of interpolating between 3D model snapshots. Our current thinking is that such models cannot easily be interpolated, because transitions are either complex gradual changes (*e.g.* progressive deterioration) or practically instantaneous in relation to the lifespan of a feature (such as additions or destruction). In the first case, detailed knowledge and modelling of the processes would be required; in the second case, it is merely a case of identifying the date of change.

Consequently we expect to model 3D objects as a set of groups of 3D primitives, each group having a specified lifespan overlapping with other groups. Changes in fabric or detail can be modelled by replacement of one group with another in the same location, or through attached attributes.

2.5 Recording fuzzy data

We are using the term *fuzziness* as a general term to describe a number of different phenomena, as follows:

Spatial

Uncertainty - We don’t know exactly *where* an object was located. Spatial uncertainty may arise from inadequate data (*e.g.* mapping a feature from isolated observations) or imprecision in the records (generalised statements of location in historic records without specific geographic references).

Diffuseness - The edge or position of an object is poorly defined. Spatial diffuseness reflects natural and cultural phenomena, such as cultural influences, which often do not have sharp boundaries.

Temporal

Uncertainty - We don’t know exactly *when* an object had a particular form or was located in a particular place. Like spatial uncertainty, temporal uncertainty arises from inadequate data (*e.g.* chronology estimated from bounding dates) or inadequate reporting (generalised statements about when something occurred or roughly-dated first-hand accounts).

Diffuseness - The change from one condition to another occurs gradually rather than abruptly, so there is no identifiable transition point.

We have made a first attempt at recording these four types of fuzziness for 2D vector objects, using a simple set of textual attributes attached to feature snapshots and transitions. These attributes were chosen with ease and repeatability of data recording in mind, and they are designed to model the sort of knowledge which we often have about spatial and temporal boundaries. For temporal fuzziness we record limiting time values and a descriptive transition function (linear, early, central, late etc.). For spatial fuzziness we record a best estimate of the boundary and descriptive fall-off functions towards the interior and exterior. We are still working on defining and extending the lists and parameters of transition and fall-off functions.

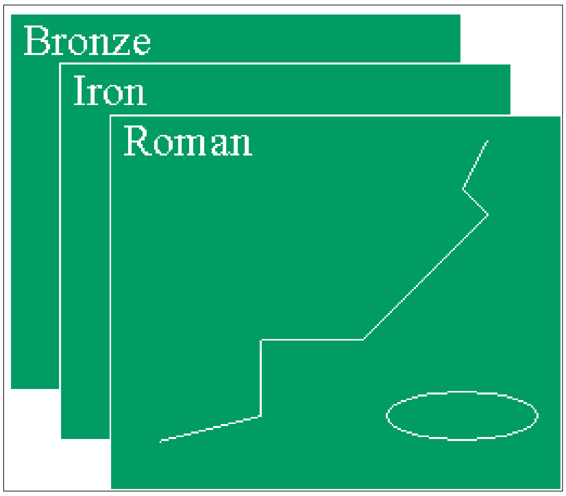
For the moment we have side-stepped the issue of recording spatial fuzziness which varies around the perimeter of an object – not because we think it is insignificant, but because there was only so much complexity we could handle at a pilot project level. The recording of varying spatial fuzziness would have greatly complicated digitising and data entry. Nor have we yet tackled the issue of interpolating between snapshots with fuzzy temporal or spatial limits, or displaying the results of those interpolations.

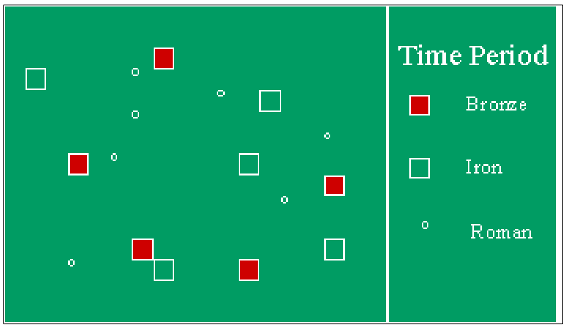
2.6 Displaying temporal data

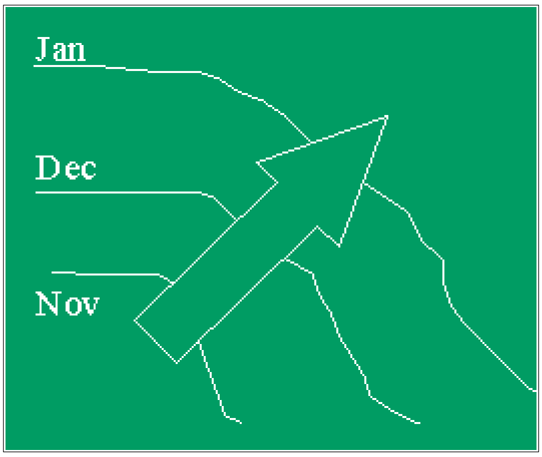
2.6.1 Traditional 2D display methods

Cartographers have developed a number of ways of squeezing extra dimensions out of two-dimensional paper maps (see Fig. 6), and these techniques are equally applied to two-dimensional computer screens. The main techniques used for representing time are:

1. Time slices
2. Symbolism
3. Arrows
4. Difference maps







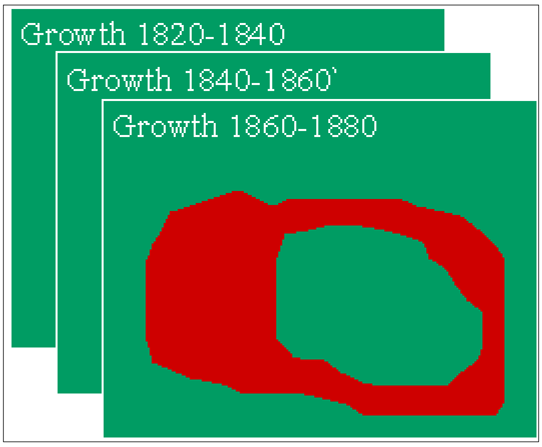


Figure 6. Traditional methods of cartographic representation: a. Time slices; b. Symbolism; c. Arrows; d. Difference maps.

While these methods can provide useful clarity in presenting specific ideas as part of an argument, none of them does justice to the underlying richness of the data, and none allows the viewer to reassess the arguments, re-examine the data critically, or ask what-if questions of it. In order to interact with the data in this way one needs a time-enabled mapping interface, such as the one we are developing for this project (section 3.2).

2.6.2 TimeMaps and animation

By displaying data in map form for a specified date or period, with immediate update when the date range is changed, one can apply a what-if mode of querying the data, and allow the creators of the underlying database to build in knowledge about transitions and transition processes which would not be available in conventional 2D maps. In addition, the use of a GIS interface, with map layers which can be superimposed and thematically coloured or shaded, provides a visually engaging delivery mode for information, which cannot be matched by conventional cartographic procedures.

An even more effective, though not *necessarily* more informative, way of presenting data on features which change through time, is to use time itself (or a modified version of time) to present the fourth dimension through animation. Animations have something of a stigma attached to them, loosely linked to Disney studios and noisy electronic games, or the vastly time-intensive products of people with more technical expertise than significant archaeological questions – in short, gee-whiz items in search of a *raison d'être*. However, I believe that, far from being necessarily so much fluff, animations have the potential to greatly enhance the display of archaeological information, particularly when dealing with data with an inherent time component. There is an increasing interest and literature on the use of animation in cartography (see for example Campbell and Egbert 1990; Monmonier 1990; DiBiase *et al.* 1992; Kraak *et al.* 1997).

While so much animation amounts to passive receipt of pre-determined products, the ideal is to provide for the combination of a time-aware map interface, which will display data for any chosen date or date range, and animation sequences generated 'on-the-fly' from the underlying database according to the user's needs. We are trying to achieve both of these aims in our TimeMap interface software (section 3.2). What is critical to the project is the notion of a *data-based* animation, not as a one-off product but as an alternative 'report format' which a user can generate from a database subset at will.

2.6.3 Static display of time-depth and fuzziness

Since one will not always wish to use animation to represent the temporal component of a dataset, we need a means of displaying time depth, in addition to other thematic characteristics of the data, on a static two-dimensional view. The problem is to find a way of displaying multiple incarnations of a single feature, or many potentially overlapping features, while still making the map intelligible. A subsidiary problem is the development of cartographic standards to represent fuzziness of spatial boundaries (borrowing techniques from standard cartographic procedures) and to represent fuzziness of temporal definition. We have not yet tackled these issues.

2.6.4 Temporal scale

An interesting problem with animation of long-term historic sequences is the punctuated nature of historical events. We encountered this problem to some degree in animating the Mongol empire, because the events which induced changes in the boundaries of the empire occur over relatively brief time spans – months or years instead of centuries. Consequently, smooth linear animation of outlines between known extents will give a misleading picture of change, while a more accurate model will result in animations which are largely static with spasmodic changes.

Ideally an animation should accurately represent the actual extents, while still displaying the transitions over a time period long enough to be grasped by the viewer. One solution to this dilemma is to explicitly change the rate of animation, so that playback speed (*e.g.* seconds per 100 years) is reduced at critical historical dates, allowing the structure of individual changes to be followed. Conversely, playback rate might be speeded up through long periods where little change occurs. Appropriate visual cues need to be developed so that the viewer is explicitly aware of the temporal 'scale' at each point of an animation.

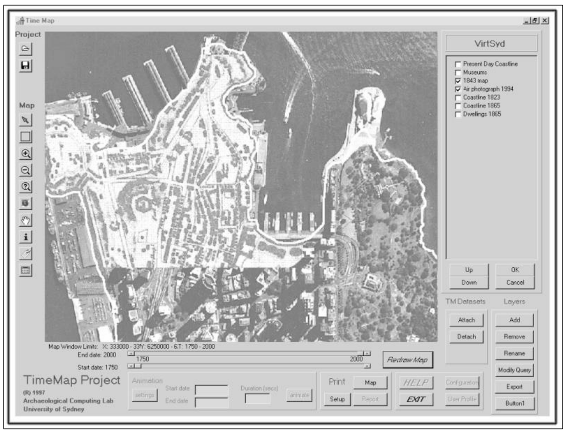
A more comprehensive approach might be developed by considering historical events to occur at a number of different temporal scales. For example, the Australian continent evolves at a time scale measured in thousands of years; colonisation spreads across the continent on a time scale measured on a more human scale of centuries or decades; the growth of the core of Sydney happens on a scale of decades or years; construction of a building occurs in months or even days; defining political events may take days or hours; actions of individuals occur at a scale of minutes or seconds; while water sparkling in the harbour does so several times per second. It is not normally possible to combine all of these temporal phenomena onto a single animation without losing fine detail of short-term events or else causing the length of the animation to blow out to the proverbial watching of grass growing.

The solution may be to overlay detail at different scales. We see the technique used, for example, in city tourist maps, where monuments of interest are drawn at a scale far beyond their real size relative to the background map. For example, the spread of Sydney urbanisation, a phenomenon occurring over a couple of centuries, might be animated at one second per year but, on top of this, short-term events such as the construction of landmark buildings or the daily commuter cycle might be represented as 'animation textures' which our eyes and brain can interpret as being at a different scale to the underlying city/landscape animation.

3 The TimeMap Project

3.1 Target applications and audiences

The methodology and software under development by the TimeMap project should have a wide variety of potential applications, and target audiences across the spectrum of computer users, from researchers to the general public. The interface we are currently developing (see Fig. 7) is rather ‘busy’, allowing researchers and curators to map and query spatio-temporal data or prepare datasets and animations for public access. Development of a public-access interface is scheduled for 1998.



☐ Present Day Coastline
☐ Museums
☑ 1843 map
☑ Air photograph 1994
☐ Coastline 1823
☐ Coastline 1865
☐ Dwellings 1865

Map Window Limits: X: 333000 - 33?Y: 6250000 - 6.T: 1750 - 2000
End date: 2000
Start date: 1750

Figure 7. The TMView software interface showing an 1843 map of The Rocks superimposed on an aerial photograph of central Sydney

Potential applications of the software include museum information terminals, where the richness of background information can be presented in a way which is not possible within an exhibition, or which requires a substantial effort of customised programming. Museums need not, of course, be restricted to buildings full of objects – the approach would be equally at home as an interpretative tool for archaeological, historical or even natural sites. Nor need they be tied to a specific location – the approach could equally be used to present information about sites, regions or continents on a CD-ROM (as we see in the current generation of CD atlases and encyclopaedias) or across the Internet.

What distinguishes the TimeMap project is that it has no specific target application in mind. Because it is based around relational database and GIS technology, rather than being end-product display-oriented, it is flexible and open, allowing the application of GIS-based tools to go beyond the features actually programmed into the interface. While this means it may be rather less slick than a purpose-built display program, it means that it is immediately portable to new sets of data without expensive and time-consuming reprogramming. Our thinking is targeted at general, robust solutions to shared problems rather than quick, specific solutions to a particular set of data. This also gives us the luxury of researching general theoretical and methodological issues of data modelling, manipulation and display which might not be appropriate to more immediate product-oriented developments.

Some of the possible areas of application of the TimeMap methodology and software include:

1. Coastline evolution
2. Climate change
3. Expansion & decline of empires
4. Settlement patterning on a landscape
5. Settlement layout and urban growth
6. Trade routes and exchange
7. Military campaigns and battles

3.2 Map display front-end ("TMView")

We have developed a prototype TimeMap front-end for Windows 95/NT using Borland Delphi as the development environment and MapInfo as an OLE Automation server to plot maps within the map window (see Fig. 7). The choice of MapInfo as a mapping tool was purely pragmatic, based on cost and availability – the next phase of our project will see us assessing a range of different mapping products, including GeoMedia Objects, MapObjects, MapX and other toolkits from the smaller players, in search of the best price/performance ratio. In practice our requirements for the mapping toolkit are fairly modest because much of the work is done within Delphi (mapping function is merely required to display a layered map and return mouse actions and object information). Cost considerations such as royalty-free runtime licensing may therefore play a critical role in our choice.

Data for snapshots and transitions is currently stored in local MapInfo and dBase format files, but the use of our metadata definition at all levels, including local storage, should allow for a smooth transition to remote SQL server databases. We are in the process of upgrading the software from Delphi 2 Professional to Delphi 3 Client-Server and transferring some datasets to Sybase on a remote computer for testing. We hope to complete this stage of the project by the end of 1997.

When TMView opens a TimeMap project, it reads a list of TimeMap datasets which it then opens for access ("attaches"). TimeMap datasets are databases which conform to the minimum standard for a TimeMap dataset and incorporate a metadata file (section 3.3), allowing TMView to access the data they contain. TMView also reads a list of SQL queries which are applied to the attached datasets in order to create the map layers which it displays.

It is important to note that TMView displays *queries* not datasets. When the time period of interest is changed by moving the slider bar underneath the map window, TMView simply updates the time selection criteria in each of the queries and redisplays the map accordingly.

The front-end currently allows the following functions:

1. Open/save TimeMap project (specifies datasets, layers, zoom etc.)
2. Pan, zoom in/out/full extent/specified window, reorder layers
3. Attach/detach TimeMap dataset
4. Create new map layer from a TimeMap dataset (through an SQL query dialogue)
5. Save map layer as local TimeMap dataset
6. Set time limits for map display and update map
7. Query object(s) on map and obtain attached attribute information
8. Print current map

Several functions planned for the prototype are still under development, but should be completed before the end of 1997. These include:

1. The ability to show a map key and change map symbology (at present the symbology used is simply the default symbology set within the original data files);
2. Access to remote datasets across the Internet;
3. Linking of map features to sites on the WWW, such as museum home pages or specific records within an on-line museum register;
4. Animation of map content through a specified time period.

These planned features are illustrated in some of the figures in this paper (see Figs. 2 & see 8) – while the underlying map interface is fully functional, the overlying browser and animation windows are "artist's impressions".

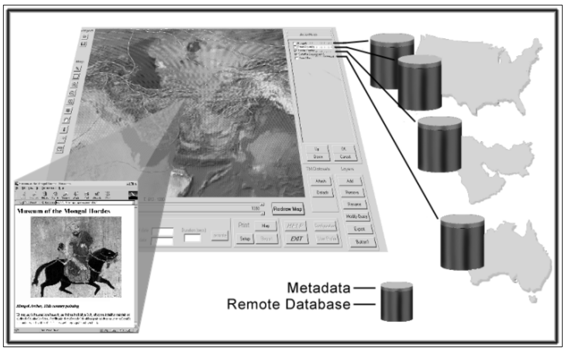


Figure 8. Creation of data layers through querying remote datasets across the Internet. Objects on the map can be further linked to WWW resources.

3.3 TimeMap metadata standard

The key to TimeMap connectivity is a metadata file which interprets the data in an existing database to the TMView software. The database must meet minimum standards – essentially a geographically located graphical object in an interpretable format and an attached date field – although it may well go beyond those minimums. Any dataset which meets the minimum standards and exposes a metadata file can be considered a TimeMap dataset.

The metadata file can be stored as a simple text file, but it is more likely to be a table in a database mounted on an SQL server, which also contains the main dataset (see Fig. 8). It specifies such information as database type, table names, field names, field values and their equivalencies so that, for example, TMView knows that it will be looking for *Date_of_accession* in the table *Stoffer_collection* when it is after the date field for an object incarnation.

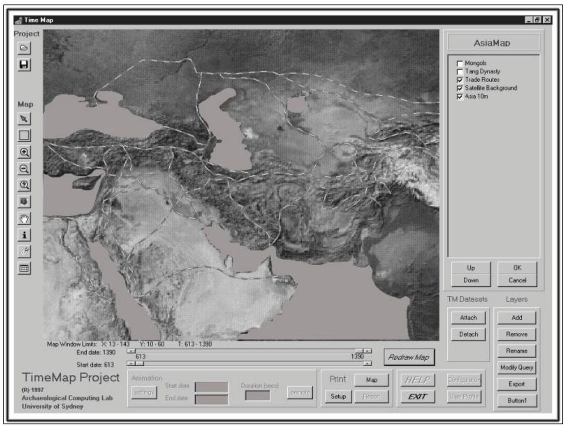
A metadata file or table can be added to an existing database, provided it contains appropriate data, without impinging in any way on normal operation of the database. Since TMView does not write anything to the source database, it does not have any implications for data integrity or for security, other than general read-access restrictions.

4 Application projects

We are currently working on two main application projects (*AsiaMap* and *Virtual Historic Sydney*) using the TimeMap methodology and TMView software. Progress on these projects is closely linked with the development of the methodology, and feedback from them influences the direction of TimeMap research. Because they are quite different projects they pose contrasting problems, which helps to point out holes in our thinking.

4.1 AsiaMap

The AsiaMap project, directed by Roland Fletcher, aims to apply the methodologies developed by the TimeMap project to mapping the spread and collapse of Asian empires. This involves a considerable amount of background research through historical documents, atlases and syntheses, although some areas and periods are extremely well-known (in particular the history of China which has been extensively mapped in *The Historical Atlas of China* (Tan Qi Xiang 1982 - 1987)).



☐ Mongols
☐ Tang Dynasty
☑ Trade Routes
☑ Satellite Background
☑ Asia 10m

Figure 9. The TMView front-end to the AsiaMap database.

To date, empire limits have been identified and entered for the Mongols and the Tang (Figure 9), and historical research is underway on the Indian empires and the growth of Baghdad. The project is also starting to flesh out the data with city plans, historical accounts, images and records of objects in museum collections. Using the digitised extents of the Mongol empire, the project has created animations (see Figs. 5 and 10) superimposed on a composite satellite base.

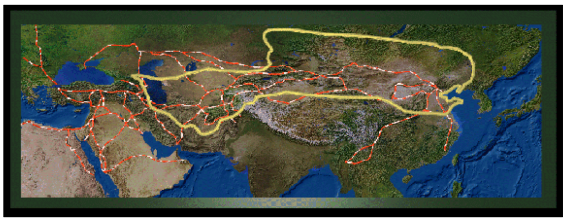
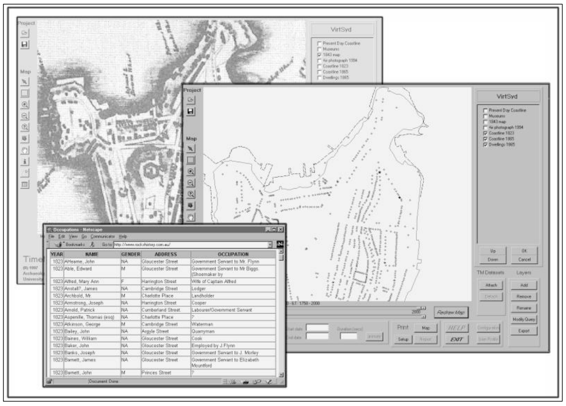


Figure 10. AsiaMap project – Frame from animation showing trade routes of the Silk Road and the extent of the Mongol Empire in AD 1231, superimposed on a composite satellite base (courtesy WorldSat International Inc.).

4.2 Virtual Historic Sydney

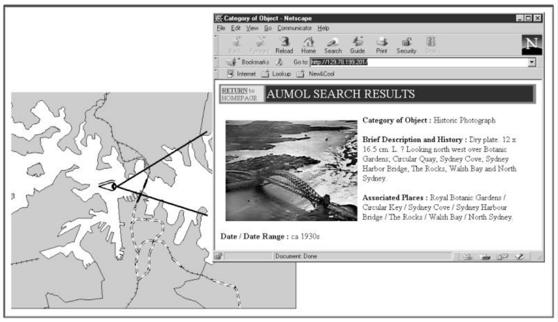
The Virtual Historic Sydney project aims to record and present urban development and historical information relating to Sydney in the 18th, 19th & early 20th centuries. We are currently concentrating on data collection for the historic core of the city. Our first steps have included digitisation of a modern topographic base map, creation of a digital elevation model and registration of available historic maps into the system. Overlain on this we have a set of 19th century occupant records (see Fig. 11) and we are working on the assembly of a variety of other resources, including engineering and administrative plans and records, written accounts, drawings and photographs, excavation records, museum collections and syntheses.



YEAR	NAME	GENDER	ADDRESS	OCCUPATION
1823	AHearne, John	NA	Gloucester Street	Government Servant to Mr. Flynn
1823	Able, Edward	M	Gloucester Street	Government Servant to Mr Biggs. (Shoemaker by
1823	Alfred, Mary Ann	F	Harrington Street	Wife of Captain Alfred
1823	Anstall?, James	NA	Cambridge Street	Lodger
1823	Archbold, Mr	M	Charlotte Place	Landholder
1823	Armstrong, Joseph	NA	Harrington Street	Cooper
1823	Arnold, Patrick	NA	Cumberland Street	Labourer/Government Servant
1823	Aspenille, Thomas (esq)	NA	Charlotte Place	?
1823	Atkinson, George	M	Cambridge Street	Waterman
1823	Bailey, John	NA	Argyle Street	Quarryman
1823	Baines, William	NA	Gloucester Street	Cook
1823	Baker, John	NA	Gloucester Street	Employed by J.Flynn
1823	Banks, Joseph	NA	Gloucester Street	Government Servant to J. Morley
1823	Barnett, James	NA	Gloucester Street	Government Servant to Elizabeth Mountford
1823	Barnett, John	M	Princes Street	?

Figure 11. The TMView software interface showing a historic map of central Sydney, coastline change and data on house occupants in the 1860s.

In a co-operative project with the Australian Universities Museums Online project (AUMOL) we are setting up a TimeMap dataset for historic photographs (see Fig. 12) held by the Macleay Museum and accessible through the AUMOL catalogue on the WWW. The database will run on a Sybase SQL server and will be our first test of linking to external data sources.



AUMOL SEARCH RESULTS

Category of Object : Historic Photograph

Brief Description and History : Dry plate. 12 x 16.5 cm. L. ? Looking north west over Botanic Gardens, Circular Quay, Sydney Cove, Sydney Harbor Bridge, The Rocks, Walsh Bay and North Sydney.

Associated Places : Royal Botanic Gardens / Circular Key / Sydney Cove / Sydney Harbour Bridge / The Rocks / Walsh Bay / North Sydney.

Date / Date Range : ca 1930s

Figure 12. Historic aerial photograph of Sydney Harbour Bridge from the AUMOL web site and area-of-view map.

5 Conclusion

5.1 Future directions

In this paper I have attempted to outline some of the issues associated with recording archaeological and historic data in a spatio-temporal context, together with the research of the TimeMap project team into practical methods of handling such data. Temporal GIS is a complex field, with many ramifications and many potential avenues of research; but I believe there are opportunities to make substantial progress and generate useful practical solutions by defining the problems clearly and tackling them in a pragmatic fashion.

In designing the TimeMap project we have concentrated on the core issue of providing an explicit and robust methodology for recording spatio-temporal features, while knowingly side-stepping issues which might distract us from the goal of a workable spatio-temporal mapping system. By identifying these issues as we proceed, we can isolate them as potential independent research projects whose completion, or non-completion, will not hold up the main project.

Our investment in thinking through the issues has paid off at the implementation stage. We have made substantial progress on the development of the interface software, TMView, in a very short time frame, generating interest which we hope will translate into funding for the continuation of the project. The AsiaMap and Virtual Historic Sydney projects are also capitalising on the existence of prior expertise/work and software from the TimeMap project as a basis for grant applications.

Ongoing information on the TimeMap, AsiaMap and Virtual Historic Sydney projects will be maintained on the School of Archaeology website at: http://www.archaeology.usyd.edu.au/research/

Acknowledgements

The TimeMap project is a co-operative effort. Roland Fletcher directs the AsiaMap project and has been the driving force behind the animation work. Pat Caldon developed the Mongol animations, assisted by Sam Moody and Sugandha Johar. Reba Kearnes has done most of the TMView interface development. Steven Hayes is responsible for Internet connectivity and database design aspects of the project. Andrew Wilson supervises data collection for the Virtual Historic Sydney project. Peter Revelant and MacLaren North maintain the ACL network and workstations. I am particularly indebted to Steven Hayes for his comments on the paper and to Steven Hayes and Andrew Wilson for assistance with preparing illustrations at short notice and shouldering additional responsibilities.

I would also like to thank Torsten Madsen and Jens Andresen, whose invitation to spend two months as a visitor at the Moesgaard Institute for Prehistoric Archaeology (University of Aarhus) gave me the opportunity to escape from everyday crisis management and organise my thoughts. That breathing space, together with lively discussions on data management and computer mapping issues, spawned the design of the TMView software and allowed me to sort out and systematise my mess of unstructured ideas.

The TimeMap project has been generously funded by the University of Sydney Pro-Vice-Chancellor for Research, Professor Roger Tanner, and supported by the Archaeological Computing Laboratory infrastructure, funded through University of Sydney Large Equipment, Research Infrastructure and High Performance Computing and Visualisation grants. The satellite base for Asia was kindly provided by WorldSat International Inc. of Toronto

Notes

1 TimeMap is a registered trademark of Roland Fletcher, University of Sydney.

2 While the feature space of a conventional GIS is continuous in x and y (any value of y within the space can and does exist for any value of x) only a single value of z exists for any given x,y. Variants with multiple z values are of course possible, but it remains that the z space is not continuous for a given x,y (z is merely an attribute of a feature, whether it be the surface of the earth or a feature on, above or below that surface).

3 *Features* are any object, whether physically materialised (such as an island, building or road) or conceptual (such as the Mongol empire or a named settlement), which has a continuous identity through some finite period of time but may change in physical extent and/or attributes.

4 Conventional 2D GIS can be used to digitise and record attributes for 2D vector objects on time-slice or thematic maps. Raster objects can be resampled and stored with associated geographical registration information. In the case of 2D vector or raster objects, each incarnation is linked to the corresponding feature record by a foreign key holding the feature ID, and each incarnation is temporally exclusive of other incarnations of that feature. Three-dimensional objects can be decomposed into primitives, with or without texturing, and stored in the database as co-ordinate sets; the model is built from groups of primitives, each of which has its own time-line which may or may not be temporally exclusive of other groups belonging to the same feature.

5 The snapshot-transition model serves our purposes well, although it would probably not be appropriate if we were attempting to develop a full temporal GIS. Langran (1992) rejects an uncomposited approach to recording spatio-temporal data because it is not space-exhausting and because topology changes through time, requiring complex tracking methods.

Langran proposes a model based on the decomposition of x,y space into polygons with a uniform history, so that each change in boundaries or position of features creates two or more polygons; such an approach is data intensive and, as far as I can see, does not cope well with continuous change or fuzzy boundaries. Candy (1995) uses a topological model based on Arc/Info which might well be applicable, but it is not clear how one would go about incorporating fuzziness or three-dimensional objects, nor is it obvious what advantages we would gain by adopting such a model.

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