A Framework for Supporting the Application of Qualitative Spatiotemporal Reasoning

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Abstract. Numerical approaches for representing and reasoning about information are ineffective when the data is too imprecise or uncertain. People on the other hand cope very effectively with vague information in daily life. This has motivated the field of qualitative spatiotemporal reasoning (QSTR), which focuses on coarse, qualitative distinctions between spatial and temporal entities and relations. A substantial body of work has emerged from the QSTR community, however, serious difficulties prevent a uniform and general qualitative treatment of data representing space and time. Without unifying principles there is no basis for comparing the various QSTR approaches, and it is not always clear when and how QSTR should be applied. These issues must be addressed before QSTR can be properly integrated into standard software tools and practices. In this paper the author's PhD programme is outlined, covering (a) the research aim of developing a framework for supporting the design and implementation of QSTR solutions, and (b) the research approach, which is based around the analysis of case studies, two of which are discussed.

Keywords: Artificial Intelligence, qualitative reasoning, case study.

1 Introduction

Computers and software systems rely on numerical methods for representing and processing information, which work very effectively when data is certain and precise. However uncertainty and imprecision are inherent properties of data that we gather from the physical world, and when probability distributions are unavailable or the numerical precision is not satisfactory, quantitative analysis methods break down. On the other hand people have a remarkable capacity to reason about and operate in the continuously changing physical world, considering that the information we have is necessarily vague and uncertain. In particular, people cope very effectively with everyday phenomena without resorting to detailed numerical analysis of a system or situation [1]. For example if I stay in the New Zealand sun for a short amount of time during summer, I will likely get sunburnt. I am not confident as to the exact number of minutes it might take, and I have no information about the ultraviolet dosage required to cause damage. Despite having only very limited information, it is enough for me to know how to enjoy the summer without getting hurt! This approach is called qualitative reasoning (QR) [2], where the aim is to make the smallest number of distinctions between objects and relationships in order to complete a task in a given domain [3].

To explain general qualitative reasoning for physical systems consider the task of brewing a cup of coffee. It is enough for me to observe that (a) the stove is hot, (b) the water in the coffee pot is at room temperature, and (c) if I place the coffee pot on the stove, the water will heat up and eventually boil. It is not necessary to use tools that provide numerical temperature readings, nor is any attempt made at solving numerical differential equations that model that water as it heats up. Instead, we define a set of qualitative values that describe the interesting or relevant possible water temperatures: *room temperature*, *hot*, *boiling*. Qualitative relationships are used: *in*, *on*. Finally qualitative functions describe the relationship between variables in the system: *Stove-temperature influences water-temperature*. It is then possible to answer questions like: “What conditions must be satisfied to brew a cup of coffee? What temperature should I set the stove to, so that the water will boil?”.

More specialised qualitative approaches have focused on reasoning about time, resulting in a subfield called qualitative temporal reasoning, designed to managed coarse grained causality, action, and change in a software system. A notable and highly influential example is Allen’s elegant and efficient interval calculus [4], in which a set of thirteen atomic relations between time intervals is defined, a subset of which is shown in figure 1. A composition table is provided which gives the possible temporal relations between the intervals t_1 and t_3 given relations for (t_1, t_2) and relations for (t_2, t_3), along with an algorithm for reasoning about networks of relations. For example, if:

- I brush my teeth (t_1) *before* I have breakfast (t_2), and
- I have breakfast (t_2) *before* I leave for school (t_3), then
- Brushing my teeth (t_1) must also come *before* leaving for school (t_3).

A natural progression from qualitative temporal reasoning is to consider qualitative spatial reasoning (QSR) [1, 5, 6], where relationships between objects and regions are coarsely defined and reasoned about, concerning topology, shape, orientation, and distance. QSR can be used to answer questions like: “Are there any cafés *near* the university *in* Downtown?”. However, serious doubts have been raised regarding the possibility of a systematic, unified approach to QSR known as the poverty conjecture [7], stating the belief that no qualitative description of space exists that can be used to solve tasks in a variety of domains without problem specific metrical information. Despite this, significant progress has been made in a number of subfields, for example, Region Connection Calculus (RCC) [8] is a system used to reason about the topological relationships between regions, and in a similar fashion to Allen’s interval calculus, defines a set of qualitative spatial relationships that can exist between region pairs. Figure 1 illustrates a subset of these relations. Composition tables are provided, along with algorithms to reason about networks of region relationships.

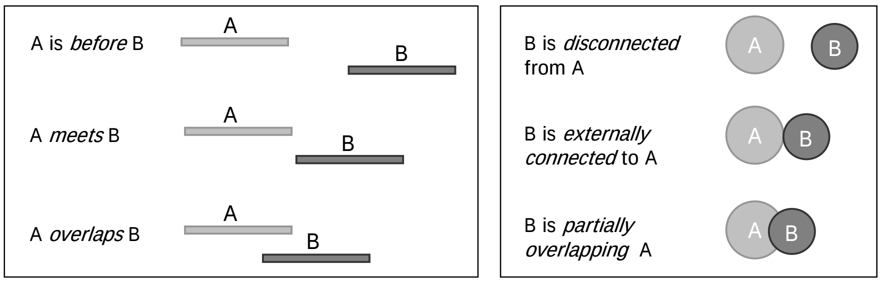

Fig. 1. Subset of the temporal relationships defined in Allen's interval calculus [4] (left), where A and B are time intervals. Subset of the region relationships defined in Region Connection Calculus [9] (right), where A and B are regions.

Methods for qualitative reasoning about time or space are collectively known as qualitative spatiotemporal reasoning (QSTR). While a substantial body of theoretical work exists in QSTR, along with a host of industrial applications, a central problem is the lack of a unified framework that provides a standard for the various formalisms and techniques [3]. For example, QSTR formalisms have been developed that work at different granularities, addressing different aspects of a problem, and it is not clear how the various approaches relate to one another, thus making it difficult for researchers to exchange and compare results [3]. The fundamental problem is that the lack of principles and approaches for integrating a QSTR solution with standard software systems [3, 7]. In some cases a qualitative approach will greatly assist in solving a problem. In other cases it may fail to reveal any insights, simply not apply to a domain, have no impact, or even complicate the problem. The author's PhD research project addresses this issue, with the overall aim of developing a framework for systematising the application of QSTR methods. The framework will be based on problem and QSTR method classification schemes, classification scheme relationships, metrics for quantifying aspects of applied QSTR, and best-practice software architecture design strategies.

2 Supporting QSTR Software Development

The overall aim of the author's PhD research is to support the development QSTR in software. The result will be a framework that acts as a practical guide for applying QSTR, aimed at software developers who are assumed to have little or no experience with the qualitative reasoning literature. Three main aspects will be addressed:

1. Making clear which qualitative technique is the most appropriate for a given type of problem
2. Establishing best-practice design methods in terms of software architecture
3. Quantifying the advantages, limitations and drawbacks of the proposed qualitative method, and, where possible, providing a means for measuring the potential benefits.

2.1 Objectives and Methodology for Developing the Framework

The tasks that are being undertaken towards the development of the proposed framework are (i) producing classification schemes for structuring the problem domain and the QSTR method domain, (ii) determining the associations between the two domains, (iii) developing metrics for assessing QSTR approaches, and (iv) establishing the most appropriate design strategies for applying qualitative methods in terms of software architecture.

In order to explore the possibilities of applied QSTR to determine the association between QSTR techniques and problems, a number of case studies are being undertaken, along with the analysis of other successful QSTR implementations. Conclusions drawn relating to the appropriate application and implementation of QSTR will direct the development of the proposed framework.

Classification schemes will be developed for classing QSTR methods and the problems that they can apply to. This is a necessary part for identifying which problems or tasks in general can benefit from a qualitative approach, and will be based on the common, salient characteristics shared across many similar problems and QSTR approaches. The schemes will specify which problems can be addressed by qualitative methods and will assist a person who is interested in exploring a qualitative solution. Furthermore, this will provide a platform for other qualitative spatiotemporal reasoning researchers to compare novel methods to existing ones. The sources of the data used for developing the classification schemes are the case studies that have been undertaken (discussed in section 3), reviewing QSTR applications in the literature, and reviewing artificial intelligence problem solving literature.

Relationships between the attributes defined in the problem and the qualitative method classifications will be determined to provide a system for associating the two domains. Relationships will be identified by considering the trends in existing qualitative applications, by reviewing qualitative formalisms, and by conducting a deeper analysis of the way in which data associated with a problem is manipulated by the qualitative approaches.

Metrics will be developed for analysing the underlying qualitative formalisms in order to determine the most suitable approach for a given task, and to verify its applicability to the problem. The effectiveness of a qualitative approach must be quantified in terms of the problem being solved so that different qualitative methods can be systematically compared. For example, important factors are the degree to which a problem has been solved and the cost incurred for applying the solution.

Integrating qualitative methods into a task environment requires a clear understanding of the software components that must exist, and how the components must interact. Without information on the best practices for software architectural design, a developer who is applying a qualitative approach may produce software that is inefficient or even faulty. Providing this information will decrease the software design and development time, and will ensure that reliable and consistent implementation results are achieved.

3 Case Studies

The application of QSTR covers a wide range of disciplines apart from physical systems, including education, economics, and ecological and social sciences. To help classify the various problems that can benefit from a QSTR approach, five application based case studies are being performed covering project management, robotics, astronomy, geographic information systems, and construction IT. The intention is to encounter, first hand, the issues that are raised when attempting to implement the proposed QSTR approaches. Case study analysis is conducted by referring to the current draft classification schemes, which are primarily based on more general artificial intelligence problem solving literature. From these case studies and other literature review based work patterns are being identified and used to refine the classification schemes and the problem and QSTR method domain associations. In the following sections, two of the five studies are presented.

3.1 Case Study: Qualitative Query Support for GIS

Modern Geographic Information Systems (GIS) commonly provide powerful tools for manipulating, viewing and querying geographic information, allowing the isolation and informative presentation of relevant spatial features from typically large volumes of data. An effective querying system must provide flexibility, to appropriately capture a user's desired search criteria, and usability, so that the system is appropriately accessible. Despite this, standard GIS querying capabilities are often very limited, (particularly many publicly accessible web-based GIS), or require a user to have knowledge in specialised areas such as Structured Query Language (SQL) or set theory. By relying on numerical analysis techniques, GIS struggle with uncertain and imprecise information. As people communicate about spatial concepts using qualitative information it is desirable that a querying system support the use of such information and uncertainty. This application area raises issues regarding human-computer interaction (HCI), reasoning given uncertain and imprecise spatial criteria, and the management of large amounts of data for qualitative spatiotemporal reasoning.

A system called TreeSap GIS [10, 11] is being developed that explores the use of QSR, and demonstrates its applicability towards more sophisticated, yet widely accessible, qualitative query support, as illustrated in figure 3.

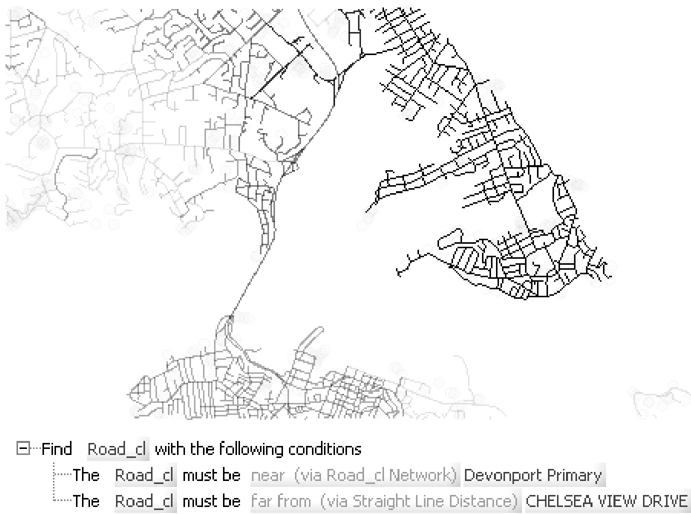

Fig. 3. Screenshot of the transparency method (top) used to visualise results of a qualitative query (bottom). The qualitative terms used to specify criteria ("very near", etc.) capture the concept of vagueness and are accessible to non-experts in GIS.

3.2 Case Study: QSTR for Subjective Lighting Criteria in Architecture

The discipline of architecture is concerned with more than simply meeting practical criteria, such as: can the building support the required load? Does the noise level, temperature, or airflow meet the appropriate health and safety standards? Architecture involves the study of how to direct a person's perception of their environment, for example, to evoke a mood, or to convey an abstract concept. This involves managing contradictory requirements that are often difficult to resolve through purely numerical analysis; an example of this is the subjective impression, or atmosphere of a space that can be evoked by lighting.

In such cases, numerical approaches for representing and reasoning about lighting related information are not satisfactory. For example, the level of detail at which processing is being performed is often inappropriate, particularly for early stages of design. Issues regarding usability are raised as an architect, for example, must manually determine whether the desired aesthetic and functional requirements from a lighting configuration are being met, having been given lists of numerical data that can involve a mixture of units (resulting from numerical simulation of a designed model). Thus, issues raised in this application area include the human-computer interaction issue of managing subjectivity, reasoning given vague information, and integrating various vague pieces of information (e.g. "dim lighting, with sharp shadows and striking highlights can evoke a dramatic and sophisticated atmosphere") into a reasoning framework.

A software system is being developed that uses a QSTR engine for analysing a lighting installation and reporting on the subjective impressions that will be evoked. A mockup of the proposed system interface is illustrated in figure 4.

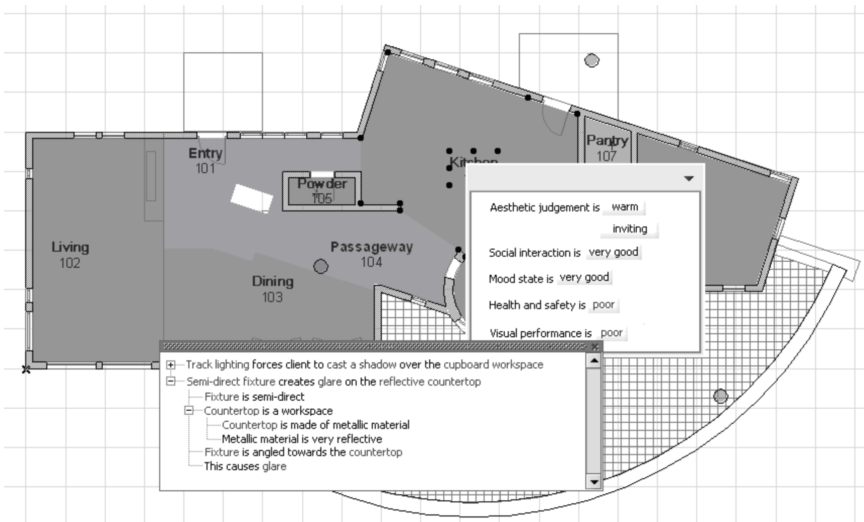

Fig. 4. Mockup screenshot of the interface used to analyse the subjective impact of a physical lighting configuration.

4 Conclusions

Qualitative spatiotemporal reasoning (QSTR) is a field of artificial intelligence motivated by the way that people handle vague and uncertain information about spatial and temporal phenomena in daily life. It addresses a number of limitations that arise when a system relies entirely on numerical methods for representing and processing data. A number of successful techniques and formalisms have emerged over the last 30 years, however a lack of design and implementation support, along with questions surrounding applicability, are hindering the field's ability to broaden its scope of application. This PhD research is focused on providing a framework that will tie the various aspects of QSTR together by identifying (a) important characteristics of the problems being tackled with QSTR (b) important characteristics of the QSTR approaches being applied, and (c) the relevant interactions between problems and QSTR solutions. The framework will act as a practical guide for developers who are assumed to be unfamiliar with QSTR literature, in particular (i) making clear which qualitative technique is the most appropriate for a given type of problem, (ii) establishing best-practice design methods in terms of software architecture, and (iii) provide metrics to assess the overall solution quality by quantifying the advantages, limitations, and drawbacks of the proposed qualitative method. Development of the framework is currently being driven by five case studies, each involving the application of a QSTR method to a problem in a particular domain. Two studies were discussed: qualitative query support for GIS, and QSTR engine for managing subjective lighting criteria in construction IT.

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