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Spatial Search, Final Report

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Spatial Search

Specialist Meeting

December 8–9, 2014

Santa Barbara, California

Final Report

Center for Spatial Studies
University of California, Santa Barbara

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Introduction

This report covers a 2-day specialist meeting on the subject of **Spatial Search** conceived and organized by the **Center for Spatial Studies** (spatial@ucsb) at the University of California, Santa Barbara (UCSB). The meeting was held on December 8–9, 2014 at the Upham Hotel, in Santa Barbara, engaging 36 international experts from academia and industry in a variety of highly interactive sessions. The event's topics, its agenda, and its outcomes are described below.

The Spatial Search meeting was one of numerous specialist meetings that have been organized in Santa Barbara over the past 25 years. The structure of these meetings combines a number of context-setting presentations, with ample time for discussion in plenary sessions, small groups, and informal social gatherings. Spatial@ucsb specialist meetings promote intensive discussion on themes related to theoretical issues, technological developments, and applications of geographical information science and spatial thinking in science and society. Such meetings are intended as catalysts for new research and teaching programs, new software developments, and funded research initiatives.

The Spatial Search Specialist Meeting

The 2014 meeting focused on the spatial aspects of information search, tackling a rich and promising interdisciplinary area. The selection of this topic was rooted in the observation that information search has become an enabler across the spectrum of human activity. Search engines process billions of queries each day and influence the visibility and accessibility of online content. Scientists search for meaningful patterns in massive data sets, while consumers search for products and services in a growing pool of options. Operating at two levels, there is a spatial component at the core of search. On one hand, search technologies rely on a spatial metaphor: We talk about going to our favorite websites to help search for fragments in an overwhelmingly large space of documents, images, and videos. On the other hand, geographic space will index information and refine search strategies, relying on the geographic location of entities to assess their relevance. While the spatial dimension of search is pervasive and foundational to many disciplines, it has not been adequately analyzed and synthesized across disciplines.

The **program chairs** for this meeting were:

- Andrea Ballatore (Research Coordinator, Center for Spatial Studies)
- Mary Hegarty (Associate Director, Center for Spatial Studies)
- Werner Kuhn (Director, Center for Spatial Studies)
- Ed Parsons (Geospatial Technologist, Google)

Funding for the event was provided by the Center for Spatial Studies, with contributions from ESRI and Google, whose support is gratefully acknowledged.

Participants were selected from a competitive pool of applicants, and four keynote speakers from academia and the industry were invited to express their perspectives. A website for the event was created to host all relevant information. The list of participants, including short biographies and position papers (http://spatial.ucsb.edu/2014/spatial-search/participants), were made available online weeks before the meeting (see Appendix for the complete listings).

Goals and Agenda

Following the successful model of previous Santa Barbara specialist meetings, using intense and focused discussion among participants, the core goal was to develop an interdisciplinary research agenda to advance spatial search from scientific and engineering viewpoints. To frame this objective, the topic of spatial information search was organized along three complementary strands—*computational*, *geospatial*, and *cognitive*—each with its own specific research questions:

Computational strand: What are the current computing challenges in spatial search? What are the limits of spatial indexing? Where are the bottlenecks? What techniques and algorithms have substantially changed the way in which we design search functionality in large information systems? Are reference systems and meta-data helpful? What is the future of spatial search models?

Geospatial strand: What kinds of spatial search are utilized in the geo-spatial domain? What search functionality is missing in current Geographic Information Systems? How can Geographic Information Science interact with other domains to promote spatial thinking and education in the context of spatial search?

Cognitive strand: What do we know about how humans conceptualize and perform information searches and how space helps? How do search technologies impact human cognition of geographic and information spaces? How do humans search memory and visual or aural stimuli? Can hypotheses and insights from the cognitive sciences and neurosciences inform computational and geospatial search techniques?

The meeting agenda was customized to maximize interdisciplinary interaction between participants and, at the same time, to target research questions as an outcome. To provide context to all participants, short presentations and interactive sessions were alternated. The complete agenda is available online (http://spatial.ucsb.edu/wp-content/uploads/smss2014-agenda.pdf). Each interactive breakout session was led by a moderator and recorded by a designated recorder; a reporter then summarized the group's discussion for the other groups.

The agenda can be summarized as follows:

Day 1 (Monday, December 8)

- Welcome and introduction
- Keynote addresses (V. Murdock and M. Eckstein)
- Breakout session A: *Searching for what?*
- Keynote addresses (R. Purves and S. Card)
- Breakout session B: *How to search?*

Day 2 (Tuesday, December 9)

- Lightning talks (R. C. Dalton, M. Graham, K. Janowicz, T. Matlock, P. Todd)
- Breakout session C: *What is the future of spatial search?*
- Perspectives on the Research Agenda (W. R. Franklin, S. Hirtle, B. Tversky, M. Yuan)
- General discussion of the Research Agenda

The remainder of this report summarizes the presentations, the participant contributions, and the notes from the breakout sessions, as well as the open discussions that were held to identify key observations and make recommendations for specific actions. With the diverse pool of participants, the views of geographers, cognitive psychologists, information and computer scientists, technologists, and industry practitioners, were well represented and served to effectively highlight knowledge gaps and research opportunities.

Keynote addresses

The contents of the four keynote addresses are summarized below. Some of the presentations are available online (http://spatial.ucsb.edu/2014/spatial-search/participants).

Vanessa Murdock (Microsoft):

Language Modeling for Places from Social Media

Murdock's presentation focused on the interactions between online and offline activities, highlighting the central role of location as a point of contact between these two spheres. Because GPS-enabled smart phones are widely used, we have an unprecedented amount of data about where people are and what they are doing and thinking at a given time. We can leverage this data directly for specific tasks, such as identifying the location a photo was taken, or more obliquely as a background model of a user's geographic context, to be used in ranking, recommendation, or prediction. One approach to harnessing geo-tagged social media is to turn it into an information retrieval problem. Murdock described a technique of segmenting the globe into "cells" and populating each cell with the social media artifacts emanating from that cell, treating each cell as a "document" and estimating a term distribution from it. This document representation of places allows us to rank places given a query, or compute a similarity function between a short text and a place (Murdock, 2014). In her work, Murdock has investigated several segmentation schemes for information retrieval tasks.

Miguel Eckstein (Department of Psychological & Brain Sciences, University of California, Santa Barbara):

Visual Search: How Does the Brain Do It?

In this talk, Eckstein reviewed the research area of visual search (Eckstein, 2011). Short visual searches are ubiquitous in human cognition, and involve moving the eyes to point the central area of the human retina (the fovea, with significantly higher resolution) to regions of interest in a scene to extract information related to the search. After covering the biological structure and constraints of the human visual system, Eckstein discussed how the brain uses peripheral processing to extract critical information and guide the eyes across a scene. Eye movements are guided by information about the searched target including basic features such as color, size, orientation, and shape. Thus, advance knowledge about the search target is instrumental. The brain is able to acquire information in the visual periphery to guide eye movements concurrent with analyses of information at the foveal region. Yet a target can often be small and difficult to detect in the visual periphery and the human brain must rely on other visual cues and on configurational knowledge to guide eye movement. Objects in the visual environment are typically not randomly located: Fruits tend to be on or under trees; plates are placed on tables; and chimneys are attached to houses. Humans have a remarkable ability to learn typical relationships among objects. Finally, Eckstein addressed how the brain uses peripheral processing of a scene and learned relationships among objects or basic features to rapidly guide eye movements toward likely target locations.

Ross Purves (Department of Geography, University of Zurich):

Geographic Information Retrieval: Are we making progress?

Purves described the research in geographic information retrieval (GIR), its achievements, and open challenges (Jones and Purves, 2008). Extracting locations from documents in the form of place names had been identified as an important challenge that had already received attention from computational linguistics as part of Named Entity Recognition. This task remains a challenging one for automated systems that typically adopt relatively simple approaches, such as using ancillary information mined from other content (e.g., population counts or co-occurrence with other terms) or simple geometric measures to calculate distances to the nearest unambiguous referent identified. The notion of indexing is central to all efficient searches, and purely text-based solutions with adequate indexing are often hard to beat. Interestingly, there seems to be little formal cross-over between work on spatial cognition and relevance ranking in GIR. Furthermore, user interfaces for geographic search have developed little beyond the prototypes of the early 2000s and the display of results in spatial search has not progressed much beyond the display of points on maps. In evaluating GIR, traditional and emerging approaches based on pooled judgments and crowdsourcing are deemed ill-suited to assessing spatial nuances in local knowledge, and the need for more qualitative user-centered evaluation for assessing long-tail queries should not be underestimated. A second key point in developing effective evaluation strategies concerns harnessing the information that can be obtained from query logs so as to better define how users actually interact with systems. Better understanding of how users formulate geographic queries, and linking this to basic notions of spatial cognition seems to be an obvious area where interdisciplinary research could rapidly bring tangible benefits.

Stuart Card (Department of Computer Science, Stanford University):

Visual Microforaging: Understanding the Rapid Acquisition of Information from Emergency Medical Checklists

Card discussed a project in the area of human-computer interaction (HCI) in the design of medical equipment. HCI often involves trading between spatial and textual representations to achieve a nuance of representation that makes a task faster to execute, easier to learn, or less prone to error. Even generally successful interfaces can still hide bad combinations of interface, task, and context that could be improved. One method of approaching this problem is to run chronometric experiments with contrasting conditions. Aside from being expensive for development work, this method is at such an aggregate level that it often does not provide much access or insight into the underlying mechanisms at work. The intent is to specify the likely mechanisms at work and to validate them by their ability to predict chronometric or other data. The validated simulator can then be put to work on inferring other consequences of the design with some claim to understanding why. While this method has advantages, it is even more expensive and is most practical for large projects or projects close to an existing model that can provide a starting point. A third method is to construct a tool that makes the mechanisms at work visible when applied to samples of user behavior. Card then described the VERP Explorer

(Visualization of Eye-Movements based on Recurrence Plots) that exploits eye-movement sequences of users performing visual-cognitive tasks with the subject system. These are mapped into recurrence plot visualizations to highlight patterns of quasi-sequential behavior (Cirimele et al., 2014). The system is applied to a sample of eye-movements generated in previous studies of the visual-cognitive task of emergency medical checklist use. Recurrence plots of other checklist designs are different, reflecting the visual-cognitive processes required to extract needed information. Many of the patterns visible in such plots can be broken down into "motifs" that signal certain types of behavior, and these patterns can be quantified by recurrence quantification analysis (RQA) and thereby aggregated and compared. A pattern of search that looks a lot like that described by information foraging theory on a miniaturized scale emerged from this study. Doctors search for an information patch using saccades (explore), then read information in the patch using fixations (exploit).

Breakout Session A: Searching for What?

The objective of this session was to quickly establish some consensus on (or at least the range of) search targets. The groups were intentionally formed to have somewhat homogeneous backgrounds rather than cross-cutting too many disciplines (which came later, in the discussion of approaches and challenges).

Suggested themes:

In your research, what is the nature of the space?

What are you searching for?

What defines spatial search?

Group 1:

Moderator: E. Parsons; Recorder: S. Gao; Reporter: K. Janowicz

Participants: M. Ali, A. Ballatore, S. Card, R. Franklin, C. Freksa, K. Grossner, Y. Hu, B. Jiang, C. Jones, W. Kuhn, A. MacEachren, V. Murdock, R. Purves K. Weimer, M. Yuan

Group 2:

Moderator: M. Hegarty; Recorder: J. Jablonski; Reporter: L. Schooler

Participants: R. Conroy Dalton, M. Eckstein. W.-F. Tat, M. Graham, D. Hardy, S. Hirtle, S. Lafia, T. Matlock, S. McDonald, G. McKenzie, J. Metelka, S.; Newsam, B. Nuernberger, S. Prasad, P. Todd, B. Tversky

Summary of discussions:

The discussions focused on the ways in which different disciplines, including geography, cognitive science, and computer science, conceptualize their spaces and search problems. The following points of discussion were identified:

- Spatial search is a broad concept that can be articulated in many alternative ways depending on one's disciplinary perspective. Useful dimensions to conceptualize spatial search are:
    - o Search for information or search for physical objects
    - o Search for particulars (a specific object) or kinds (a category of objects)
    - o Different types of spaces (geographic space, space of user interfaces, and memory space)

- Dimensionality: Geographers typically work in 2, 3, or 4 dimensions, but cognitive psychologists know that the search in the mind operates in high-dimensional spaces.
- Spatial, temporal, and thematic dimensions are always interacting in search, even though many dimensions are left implicit based on the context.
- The idea of facilitating retrieval of information when the users are not explicitly searching should be considered. Search can be also be performed for unknowns, such as open research questions, or for unexpected patterns in data.
- A fundamental difference exists between abstract search spaces that cannot be visualized in their entirety (e.g., search engines), and spaces in the physical world that humans experience directly and inhabit every day, such as visual search.
- Searches in the area of cognition tend to be based on satisficing and sub-optimal choices as opposed to the optimal decision making. Open general questions about search in biological organisms include: Do lower order organisms search? Is consciousness necessary for search? Does search need to be goal oriented?
- A distinction was made between retrieval and search. *Retrieval* occurs when a precise piece of information is found in a search space, while *search* involves more uncertainty about the existence of a piece of information. Overall, it does not seem very productive to sustain a dualism between the physical and the digital, as spaces tend to be hybrid and augmented by information sources.
- Hybrid spaces can be navigated with the help of computer vision and machine learning. Geographic spaces can be represented with images, and then using augmented reality technologies to help users navigate those spaces. Searching for information in these kinds of spaces must be more effective.
- Search technologies have a broad impact on society and its power structures. When technologies are designed, we should always ask who is empowered and who is marginalized by them in the relevant spaces. In general, more research is needed to understand how web and mobile communication technologies affect behavior and culture.
- A core challenge consists of adding a spatial dimension to text-based searches. The representation of alternative non-geometric spaces, such as music space, concept space, food space, time space, is also challenging. As these spaces are often very large and multidimensional, it is unclear what navigation techniques can be used for them.

Breakout Session B: How to Search?

The second breakout session emphasized current and future search mechanisms. Participants were divided into three groups to discuss complementary aspects of spatial search. The first group focused on spatial search as a process of question answering, while the second group discussed search with respect to algorithms, heuristics, indexing, in contrast with how humans do it. The third group discussed the evaluation of spatial search, in terms of criteria, testing, and ranking of results.

Group 1: Formulation of search questions to obtain meaningful answers

Moderator: K. Grossner; Recorder: G. McKenzie; Reporter: S. McDonald

Participants: M. Ali, R. Conroy Dalton, M. Graham, J. Jablonski, K. Janowicz, B. Jiang, S. Lafia, S. Prasad, R. Purves, M. Yuan

Group 2: Optimization of search (algorithms, heuristics, indexing, how humans do it)

Moderator: C. Freksa; Recorder: Y. Hu; Reporter: T. Matlock

Participants: S. Card, R. Franklin, S. Gao, M. Hegarty, S. Hirtle, W. Kuhn, S. Newsam, P. Todd, B. Tversky

Group 3: Evaluation of search results (e.g., criteria, testing, ranking)

Moderator: A. Ballatore; Recorder: K. Weimer; Reporter: W.-T. Fu

Participants: M. Eckstein, D. Hardy, C. Jones, A. MacEachren, J. Metelka; V. Murdock, B. Nuernberger, E. Parsons, L. Schooler

Summary of discussions:

The first question that arose was, "What do we want to optimize?" The discussion touched on how spatial researchers have different expectations when it comes to search. Computer scientists are inclined to care more about the results of a search, while cognitive scientists have a greater concern for the process of a search. In this respect, there are differences in what counts as a space. Some of the discussion was about physical space, but not all of it. Examples of search in information spaces came up, and so did examples of "moving through" problem spaces or goal-oriented activities. In talking about optimization of search a list of primary points of interest or concerns emerged:

1) ***The role of time:*** How do we optimize utility gain per unit time?

   a) *Utility gain:* There are certain gains to be had in a search when there is high precision. Your results might be more useful and closer to what you had in mind in the end, for example, in doing a Google search. But then, sometimes you can have fun while doing a more timely, less effective search. Is there a way to we convert utility into some form of time?

   b) *Cost:* It is important to think about the cost of search time vs. the cost of comprehending the search results you obtain. In general, we must care about how much information is gained per unit of time. With any search, there are costs for the person performing the search, and for the person providing what is being searched.

   c) How to think about cost and utility in advance? The known quality of the target may play a role in deciding whether or not or how to search. But then we may not know very much about the target. We must find a balance between cost and utility gain. But then, how can we compute this into time? If we introduce UG, we have to make sure the costs are limited.

2) ***Non-spatial search:*** for example movie, similar things? Borrow ideas about how Amazon and google do searching similarity.

   a) How can we transform language descriptions into spatial similarity? In approaching spatial search, what can we learn from non-spatial search, if anything? How do we talk about non-spatial things, for example, "Is this close or far from my interests?" Can this generalize to spatial search? Use semantic similarity. Depending on the space of your use, certain options may be provided. Some services are provided but not often. People naturally fall back on what they already know. This behavior can provide benefits.

b) Place affordances for search: So, what benefits does a space afford in a search? Thinking about affordances might help limit the targets to be searched, and improve the search efficiency.
c) What does the concept of place offer? A person could think of place as a theoretical number space. That would involve going through a huge space of possibilities. Another approach involves thinking about affordances at the beginning, and use those to guide behavior.
d) Ontology can be used to represent the affordances of space. How can computers know, for example, that this room affords discussion.

2. How humans do search differently from machines? Computers have larger working memory than humans. As a result, searches that result in small cost for computers are large cost for humans, e.g., memorizing a lot of details.
   a) Humans do not generally perform optimized searches because of their biological limitations. Instead they rely on heuristics. Human searches often deliberately reduce the number of search results. We ignore a lot of information. For example, we only look at the first 10 hits in a search. Greedy approaches to finding something are computationally expensive.
   b) Proximal mechanisms provide an alternative to foraging theory.
3. Optimizing search results. Since humans have limited capability to process information, various ideas for aiding search emerged, including:
   a) Work on better visual representations of results.
   b) Identify the optimal number of results for a given search.
   c) Capitalize on information scent (as specified in Information foraging theory). Are there methods for giving hints about how valuable the information will be? Questions came up about how to measure information scent.
   d) What about other search engines? What is used to display information for users? For example, Spotlight on Mac OS X separates items into types for the user.
   e) Set size is a critical variable. Reducing the number of options is a goal of human search.
   f) Diversity of results is useful to think about. Offering clusters of information might be useful.
   g) There are also optimization paradoxes: If everyone chooses the best route, then there may be an information "traffic jam" for that route.

The evaluation of spatial search techniques is in general difficult, which may be one reason why geographic information retrieval has not improved enough. Evaluation is challenging mainly because one needs specialist knowledge of locations and spatial relations, combining expert knowledge and crowdsourcing. The discussion focused around the following themes:

1. Expert knowledge and crowdsourcing. It is possible to annotate spatial information using crowdsourcing, but since judgment is tinted by subjectivity there are issues with convergence of annotations. Moreover, there are many spatial terms that are difficult to interpret, such as near, around, etc. Qualitative evaluation techniques (for example through interviews) are possible, but it is usually very complex and costly to do.

2. Context dependency. The evaluation process is highly context-dependent, as goals and user backgrounds vary widely. For example, experts and non-experts may search and evaluate results by adopting different evaluation criteria for the relevance and quality of the results. Another illustration is found in the difference between Google Maps and Google Earth. While searches on Google Maps tend to be task-oriented, Google Earth users are mainly conducting exploratory searches, and tend to spend longer on the platform to explore different locations.
3. Exploratory search. Evaluation of exploratory search is even more challenging than task-oriented search, because it is impossible to establish objective criteria of success. It would be valuable to further develop test collections that are shared and curated and can be used across different communities to develop and test new techniques. There seems to be a lack of benchmark collections that allow evaluations to be reproduced and compared. Creation of such benchmark collections should have a high priority for all research communities involved.
4. Vagueness. Spatial search is distinctive with respect to the ambiguity of spatial terms, how distance comes into play. Notably, the definition of nearness varies depending on the context, and place name disambiguation is a difficult problem, especially for place names not encoded in a gazetteer. Spatial vagueness and ambiguity may be unique, as it not only relates to semantic ambiguity, but also to location ambiguity. Spatial relations such as containment, proximity, and adjacency are also specific to spatial search. Spatial hierarchies that intersect with these concepts could be useful for improving the search results, and could be a criterion for evaluation.
5. Spatial hierarchies and relations. As spatial search is strongly affected by scale, organizing content in hierarchies can be beneficial. However, spatial and thematic hierarchies provide a challenge for evaluation. Such hierarchies should be made explicit for the user, who can provide feedback and refine the search process. The key is to include the context in a natural way, so that search results are more relevant. A related issue lies in the evaluation of the effectiveness of spatial hierarchies and relations. Because of the relatively small part of data that's geocoded, realistic, large scale evaluation remains difficult.
6. Visual exploration. Visual search results also require evaluation. Finding specific targets is relatively straight forward, and eye movements can be collected to understand individual differences and use of search strategies. But visual exploration is hard to evaluate. Some studies asked participants to explore pictures visually, but the evaluation for such tasks is difficult. Some studies have also analyzed eye movements when people study maps, so as to understand the process of how people read and understand spatial relations represented on maps.

Lightning Talks

Ruth Conroy Dalton (Northumbria University): *Spatial Search: Semantic Structures and Subtle Signs.* Conroy Dalton discussed the topic of Space Syntax, and pointed out that hierarchy and inequalities between spaces are sources of information, and we can take advantage of the structuring of space in a smart way. Characteristics of the spatial location have a direct effect on dwell time, number of dwells, memory, speed of recall, and accuracy of remembered location.

Mark Graham (University of Oxford)*: Code, Content, and Control in Spatial Search—An Informational Right to the City.* Graham gave a perspective on the political economy of spatial search, highlighting how power structures are enforced and reproduced in the design of information infrastructures. Transparency and accountability are deemed to be missing from the current search tools that represent digitally real places.

Krzysztof Janowicz (UCSB): *Semantic Signatures for Places of Interest.* Janowicz described the IARPA Finder Challenge that focuses on the estimation of the location of pictures and videos without any explicit geolocation information. The challenge can be addressed by extracting semantic signatures from a variety of data sources, discriminating places thematically.

Teenie Matlock (University of California, Merced): *Motion Language in Spatial Search.* Matlock reported on her research on the usage of natural language to describe search on the web. She found that people frequently use spatial metaphors for talking about the web. People describe pages as places, and search as motion. Her analysis of language about the web over the past 20 years indicated that some spatial language has remained the same and some has changed. Specifically, the use of motion verbs to describe search has decreased.

Peter Todd (Indiana University): *People Search in Memory like Animals Forage in Space*. Todd covered information foraging, investigating the similarities and differences between search for food in physical spaces and search for information in virtual spaces. Semantic knowledge is organized in patches, and it is possible to model and predict how individuals move from one patch to another in exploration tasks.

Breakout Session C: What is the Future of Spatial Search?

The third and final breakout invited forward-looking, innovative perspectives on search, providing a set of four themes to inform future research.

Suggested themes:

What problems should spatial search be able to solve?

What limitations exist that prevent us from effective search?

Are advances in computing power solving the search bottlenecks?

What are innovative search paradigms?

Group 1:

Moderator: K. Janowicz; Recorder: K. Koehler; Reporter: A. MacEachren

Participants: A. Ballatore, M. Eckstein, M. Hegarty, T. Matlock, L. Schooler

Group 2:

Moderator: R. Purves; Recorder: M. Ali; Reporter: C. Jones

Participants: R. Franklin, M. Graham, S. Hirtle, S. McDonald, E. Parsons, K. Weimer

Group 3:

Moderator: W. Kuhn; Recorder: D. Hardy; Reporter: P. Todd

Participants: S. Card, C. Freksa, K. Grossner, Y. Hu, G. McKenzie, M. Yuan

Group 4:

Moderator: S. Prasad; Recorder: B. Nuernberger; Reporter: S. Newsam

Participants: R. Conroy Dalton, W.-T. Fu, J. Jablonski, V. Murdock, B. Tversky

Summary of discussions:

The participants identified a number of open challenges for spatial search that deserve fresh investigation and research. A framework was proposed, based on a table of abstract objects in physical spaces and physical objects in abstract spaces (see Table 1).

		Containing Space	
		Physical	*Abstract*
Object	*Physical*	Geographic	Where cities fall in ideological space
	Abstract	Where ideas arise	How ideas are related

Table 1: A framework with which to think about spatial search

1. Unstructured spaces. Current spatial search is confined to structured spatio-temporal data, and ideally search should be possible across large volumes of unstructured spatial data. Subjective experiences and opinions (the "subjective layer") can be included in the search space. Possible spatial questions to be asked in this space include: What emotions were present in Santa Barbara yesterday? Can we answer this sentiment space question now? What hotels are similar to the Upham Hotel in Los Angeles? First of all, solving this challenge requires the reduction of disparate data into a common spatial and semantic framework. Subsequently, because of the subjective nature of emotions, a metric of happiness must capture variation between individuals.
2. Semantic reference systems. Zoomable maps and time sliders provide a widely used mechanism to explore information structured in geographic space, but what about abstract spaces? In such cases, we need semantic reference systems and some form of ontological organization. While top-down conceptualizations help organize space at a coarse level, less is known on how we can build fine-grained conceptualizations for organizing conceptual spaces. In this context, the metaphor of map projection can be used to understand how we can represent abstract spaces, guiding the development of coordinates systems, and the assessment of distortions. Given that abstract spaces are culturally embedded, this task is very difficult.
3. Co-occurrence. A crucial component of spatial search concerns co-occurrence of objects and events in space and time, which is challenging when facing very large and heterogeneous data sources. In this sense, the space to be searched is that of interaction between entities, with a strong social and ecological component. The perspective of time geography could emerge as a new frontier for spatial search.

4. **Connectivity.** Drawing connections and relationships between different kinds of spaces would be very valuable, connecting physical and abstract spaces. A fruitful approach involves the computation of distances between entities in the geographic space, and distances in abstract spaces between the same entities, for example, mapping red states and blue states in the political space. Possible approaches include either Stuart Card's VERP visualization or the GeoVista tool to look at relations in one space and how they map onto another space.
5. **Similarity.** Current spatial search is restricted largely to exact match over structured data. A worthy aspect is that of similarity search, for example looking for similar places or similar objects in a search space. The definition of similarity is primarily context-dependent, and therefore personalization and user feedback is essential to build effective similarity-based search systems. Similarity search is conceptually related to search by analogy, which consists of identifying, for example, the "Santa Barbara of France," show me the analog of Muenster without rain. As search occurs in a mix of geographic, temporal, and thematic information, spatial search should be able to integrate and combine these dimensions.
6. **Negative and neighborhood queries.** Search approaches focus on asserting the presence of a characteristic. By contrast, negative queries aims at identifying entities that do not present a given characteristic (e.g., "where is there a place without night clubs"), and have received very little attention. Similarly, queries involving neighborhoods are still very hard to handle. Some of these problems might be solved by appropriate spatial and thematic annotation of the data, but the handling of fuzzy entities like neighborhoods require more research.
7. **From space to place.** The notion of place is very rich and complex, and yet we cannot search for places beyond very few and simple thematic dimensions. Platial models are needed to include the notion of place into geographic information systems, which are traditionally built on geometric spaces. The challenges to place-based computing include the *ad hoc* nature of places, whose definition changes depending on user context.
8. **Spatial recommendation.** Spatial search can be greatly enriched by spatially-enabled recommender systems, suggesting similar and related entities to the user. Using information foraging theories, exploratory search can be supported by structuring information in patches and suggesting when the user might want to leave a patch to explore another one. To avoid spatial "filter bubbles," i.e., the isolation of users in personalized informational contexts, stochastic elements can be introduced, varying search results with spatial serendipity.

Perspectives on the Research Agenda

The session started with overviews by W. Randolph Franklin (Rennselaer Polytechnic Institute), Stephen Hirtle (University of Pittsburgh), May Yuan (University of Texas, Dallas), and Barbara Tversky (Stanford University), followed by a general discussion of the research agenda.

Franklin highlighted two specific search problems: co-location in trajectories and locating a point in multiple polygons. He advocated keeping data structures regular, simple, and thereby powerful. Subsequently, Hirtle noted aspects of spatial search that need further research:

1. What happens if a query returns no results? How can systems help either rephrase or relax a spatial query?
2. The conjunction problem (e.g., a hotel close to an area with good kayaking).
3. The scheduling problem (a sequence of locatable tasks, such as shopping stops).
4. How can we define spatial ontologies to help us solve inferences like "find places that sell milk"?
5. How can wayfinding instructions be given in human terms?
6. How can we integrate crowdsourced results and volunteered geographic information in spatial search?
7. How can we advance user testing and evaluation?

Yuan proposed a range of directions to take for future research from a computational perspective, including:

1. We need better frameworks to conceptually organize types of search problems and representations.
2. Toponyms, gazetteers, and their cross-referencing still present open problems.
3. Search algorithms should be made explicitly spatial.
4. Similarity measures are needed for search in conceptual spaces.
5. Spatial search should support spatial and spatio-temporal relations (co-location, near, between, along, ahead, co-occurrence, etc.).

Tversky regards all search as spatial, whether geographic or conceptual. Both kinds of searches rely on proximity/similarity as well as hierarch/category. The same cognitive biases that affect search in "real" space affect search in conceptual spaces; in addition, many geographic searches are conceptually driven (e.g., restaurants). Conceptual searches are mapped to spatial ones in the brain, in language, and in graphics. We design and organize the geographic world in the same ways we organize conceptual worlds, by categories, hierarchies, order, cycles, repetitions, symmetries, 1-1 correspondences, embeddings, and networks. The crucial issue is the (mental) structure of the selected search space. There are multitudes of spaces; which one is selected depends on goal(s)of the search. The organization of the space determines inference, behavior, and innovation. We often find things without looking. Enormous efforts are currently devoted to finding specific pieces of information like restaurants. We need to devote efforts to enable searches for new ideas.

Finally, the closing plenary discussion focused on the identification of future research directions on spatial search. Multiple research questions and themes for different research communities were deemed potentially rewarding and worthy of further investigation:

Visualization. New methods must be developed to provide a better organization of knowledge beyond lists of links and traditional pins-on-maps. Understanding mental representations of geographic and conceptual spaces is essential to advance visualization.

Information summarization. How can we summarize and visualize large quantities of spatial information?

Information universe. Spatial search is fundamental to explore the information universe as a space, furthering our understanding of how space and time act as fundamental ordering principles.

Analogy and similarity. Development of analogy-based and similarity queries for places (e.g., find places similar to Santa Barbara in Europe).

Relations. New methods are needed to assemble and visualize related things together in a search space.

Search as a process. The current focus for navigation is on egocentric models. Search should be seen as a process, including the linguistic aspect.

Search as push or pull: Information foraging can inform the design of alert/push search systems, with many potential application areas.

Spatial understanding. Do the computational tools improve or impoverish our spatial understanding? The effects of spatial search technology should be researched more extensively.

Information retrieval. The information retrieval community still ignores space and place, and more efforts from GIScience are needed to make space and place central to search.

Social aspects. Beyond economic incentives, what are the socially most useful questions to ask, searches to support? How are search technologies impacting social inequality?

Digital Humanities. The emerging area of the Digital Humanities can provide novel data sources and scenarios for spatial search (see Geo-Humanities SIG http://geohumanities.org).

Georeferencing quality. Better evaluations of georeferencing and geoparsing are needed to support spatial search effectively. Much of the online data is not spatially encoded.

Improving data models. Mainstream search engines need better topological and geographic models to produce meaningful results. See for example http://www.wolframalpha.com.

Subjective layer. Data about subjective judgments should be included in search, for example by enabling emotion and sentiment analysis.

Semantic Web. How can the use of Semantic Web technologies and models support spatial search? Spatial search in linked open data is also an important challenge.

Deep web. Tapping the deep web spatially can unleash resources, leading to unexplored data silos. To date, only specialized and ad hoc solutions exist to delve into the deep web. The geospatial dimension is opaque and is limited to a niche.

Spatial indicators. Publicly available spatial indicators can inform search and comparison of places (e.g., Walk Score http://www.walkscore.com).

Searching with questions. Questions and dialogue represent an alternative search paradigm that is emerging.

Evolution of users. Systems and corpuses are evolving nicely. But do we know how people are evolving? We need empirical data with a spatial lens on this. How are we adapting to search environments?

Tyranny of space. Can spatial search help break down the "tyranny of space" for users and re-assemble content flexibly?

Search for events. Spatial search should include answering questions about where events are/were/will be, asking *when* questions in space.

Conclusions

This specialist meeting provided a platform for a discussion of spatial search and its many facets, gathering a diverse group of 36 experts from academia and industry over two days. The discussions identified several research gaps that will require broad interdisciplinary efforts over the next five to ten years. Research in cognitive psychology should further illuminate the strategies and heuristics deployed in search behavior in physical and information spaces, deepening our understanding of how humans search for patterns in stimuli and in memory, bringing information foraging and alternative paradigms to the next level. Computer science can provide new search frameworks, techniques, and interfaces, taking into account the geo-spatiality of the data more explicitly, while geography can benefit from new search approaches to explore data and formulate new research questions. A special issue in the *Spatial Cognition and Computation* journal will provide a more formal outlet to further develop this agenda, fostering research collaborations among participants. In conclusion, consensus was established on the central role that spatial thinking and computing should play in studying and improving spatial search for information over the next decade.

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Meeting Agenda

Spatial Search

December 8–9, 2014
Upham Hotel, Santa Barbara

Sunday, December 7: Arrival Day

Participants arriving throughout the day
Happy Hour at the Upham lobby at 5:00 p.m.; groups may organize for dinner at 6:00 p.m.

Monday, December 8: Day 1

8:00 am Check in, Garden Room

8:30 Welcome and Introductions
Overview of Goals: A. Ballatore, M. Hegarty, W. Kuhn (UCSB); E. Parsons (Google)

9:00 **Keynote Addresses:**
Vanessa Murdock (Microsoft): *Language Modeling for Places from Social Media*
Miguel Eckstein (UCSB): *Visual Search: How Does the Brain Do It?*

10:30 *Break*

11:00 **Break out Session A: Searching for What?**
In your research, what is the nature of the space?
What are you searching for?
What defines spatial search?
Group 1: Garden Room
Moderator: E. Parsons
Recorder: S. Gao
Reporter: B. Jiang
Participants: M. Ali, A. Ballatore, S. Card, R. Franklin, C. Freksa, K. Grossner, Y. Hu, K. Janowicz, C. Jones, W. Kuhn, A. MacEachren, V. Murdock, R. Purves, K. Weimer, M. Yuan
Group 2: Board Room
Moderator: M. Hegarty
Recorder: J. Jablonski
Reporter: L. Schooler
Participants: R. Conroy Dalton, M. Eckstein. W.-F. Tat, M. Graham, D. Hardy, S. Hirtle, S. Lafia, T. Matlock, S. McDonald, G. McKenzie, J. Metelka, S. Newsam, B. Nuernberger, S. Prasad, P. Todd, B. Tversky

12:00 p.m. *Lunch: Louie's, served in the garden, Upham Hotel*

1:00 Demos in Garden Room

1:30 **Reports from Session A Breakout Groups**
Reporter, Group 1: B. Jiang
Reporter, Group 2: L. Schooler

2:00 **Keynote Addresses:**
Ross Purves (University of Zurich): *Geographic Information Retrieval: Are we making progress?*
Stuard Card (Stanford University): *Visual Microforaging: Understanding the Rapid Acquisition of Information from Emergency Medical Checklists*

3:30 *Break*

4:00 **Break out Session B: How to Search?**

Formulation of search questions to obtain meaningful answers

Group 1: Garden Room
- **Moderator:** K. Grossner
- **Recorder:** G. McKenzie
- **Reporter:** S. McDonald
- **Participants:** M. Ali, R. Conroy Dalton, M. Graham, J. Jablonski, K. Janowicz, B. Jiang, S. Lafia, S. Prasad, R. Purves, M. Yuan

Optimization of search (algorythms, heuristics, indexing, how humans do it)

Group 2: Board Room
- **Moderator:** C. Freksa
- **Recorder:** Y. Hu
- **Reporter:** T. Matlock
- **Participants:** S. Card, R. Franklin, S. Gao, M. Hegarty, S. Hirtle, W. Kuhn, S. Newsam, P. Todd, B. Tversky

Evaluation of search results (e.g., criteria, testing, ranking)

Group 3: Coach Room
- **Moderator:** A. Ballatore
- **Recorder:** K. Weimer
- **Reporter:** W.-T. Fu
- **Participants:** M. Eckstein, D. Hardy, C. Jones, A. MacEachren, J. Metelka V. Murdock, B. Nuernberger, E. Parsons, L. Schooler

5:00 *Wine and Cheese reception, Upham Hotel lobby*

6:00 *Dinner: Opal Restaurant, 1325 State Street*

Tuesday, December 9: Day 2

6:00–8:30 am *Hike in the Santa Barbara foothills with Don Janelle (optional)*
Please sign on sign-up list

9:00 am **Reports from Session B Breakout Groups**
- **Reporter, Group 1:** S. McDonald
- **Reporter, Group 2:** T. Matlock
- **Reporter, Group 3:** W.-T. Fu

10:00 **Lightning Talks**
- **Ruth Conroy Dalton** (Northumbria University): *Spatial Search: Semantic Structures and Subtle Signs*
- **Mark Graham** (University of Oxford): *Code, Content, and Control in Spatial Search—An Informational Right to the City*
- **Krzysztof Janowicz** (UCSB): *The Semantics of Spatial Search*
- **Teenie Matlock** (UC, Merced): *Motion Language in Spatial Search*
- **Peter Todd** (Indiana University): *People Search in Memory like Animals Forage in Space*

11:00 *Break*

11:30 **Break out Session C: What is the Future of Spatial Search?**

What problems should spatial search be able to solve?
What limitations exist that prevent us from effective search?
Are advances in computing power solving the search bottlenecks?
What are innovative search paradigms?

Group 1: Garden Room
Moderator: K. Janowicz
Recorder: K. Koehler
Reporter: A. MacEachren
Participants: A. Ballatore, M. Eckstein, M. Hegarty, T. Matlock, L. Schooler

Group 2: Board Room
Moderator: R. Purves
Recorder: M. Ali
Reporter: C. Jones
Participants: R. Franklin, M. Graham, S. Hirtle, S. McDonald, E. Parsons, K. Weimer

Group 3: Coach Room
Moderator: W. Kuhn
Recorder: D. Hardy
Reporter: P. Todd
Participants: S. Card, C. Freksa, K. Grossner, Y. Hu, G. McKenzie, M. Yuan

Group 4: Upham Hotel garden
Moderator: S. Prasad
Recorder: B. Nuernberger
Reporter: S. Newsam
Participants: R. Conroy Dalton, W.-T. Fu, J. Jablonski, V. Murdock, B. Tversky

12:30 p.m. *Lunch: Louie's, served in the garden, Upham Hotel*

1:30 **Reports from Session C Breakout Groups**

Reporter, Group 1: A. MacEachren
Reporter, Group 2: C. Jones
Reporter, Group 3: P. Todd
Reporter, Group 4: S. Newsam

2:30 *Break*

3:00 **Perspectives on the Research Agenda**

W. Randolph Franklin (Rensselaer Polytechnic Institute)
Stephen Hirtle (University of Pittsburgh)
Barbara Tversky (Stanford University)
May Yuan (University of Texas, Dallas)

3:45 **General Discussion on the Research Agenda**

5:00 *Wine and Cheese reception, Upham Hotel lobby*

6:00 *Dinner on your own in Santa Barbara*

Wednesday, December 10: Departure Day

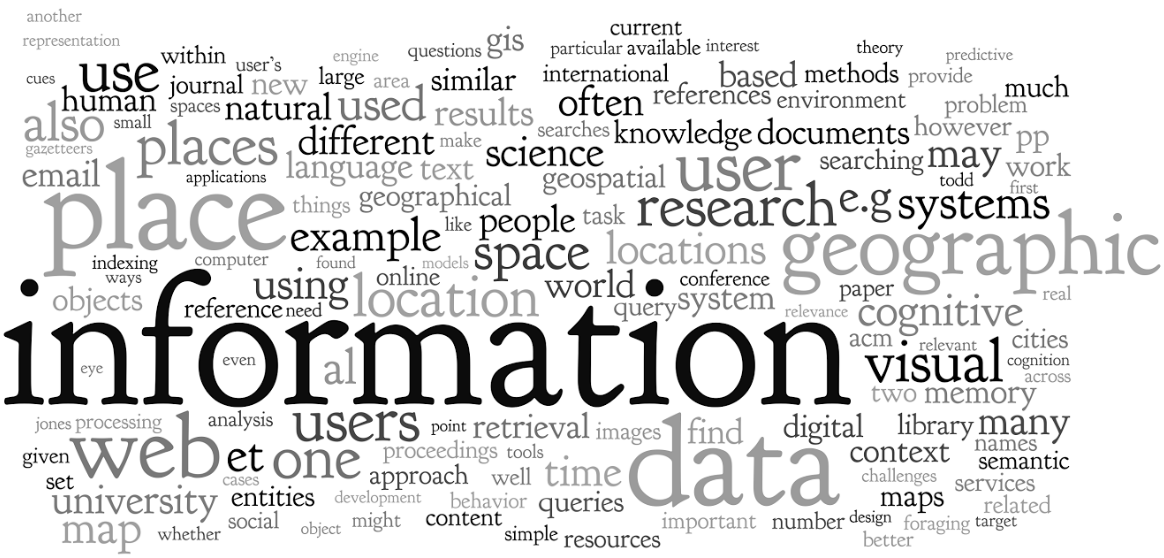
Please see Karen to arrange for transportation and logistics

Appendix B: Participants and position papers

Ali, Mohamed, et al. Purdue University	Predictive Spatial Search
Ballatore, Andrea University of California, Santa Barbara	The Search for Places as Emergent Aggregates
Card, Stuart et al. Stanford University	The VERP Explorer—A Tool for Applying Recursion Plots to the Eye-Movements of Visual Cognition
Conroy Dalton, Ruth and Jakub Krukar Northumbria University	Augmenting Intuitive Navigation at Local Scale
Eckstein, Miguel University of California, Santa Barbara	Visual Search: Guided Eye Movements for Foveated Sensory Systems
Franklin, W. Randolf and Marcus Andrade Rensselaer Polytecnic Institute	The Changing Problems, Data Bases, and Tools in Spatial Search
Freksa, Christian University of Bremen	Search in Spatially Structured Worlds
Fu, Wai-tat University of Illinois at Urbana	Guided Spatial Search in Digital Maps
Graham, Mark University of Oxford	Code, Content, and Control in Spatial Search
Grossner, Karl Stanford University	Geographic Search
Hardy, Darren and Jack Reed Stanford University	Use Cases and Personas for Spatial Search
Hegarty, Mary University of California, Santa Barbara	Cognitive Perspectives on Spatial Search
Hirtle, Stephen C. University of Pittsburgh	Geographic Information Spaces
Jablonski, Jon University of California, Santa Barbara	Spatial Search
Janowicz, Kryzsztof and Benjamin Adams University of California, Santa Barbara	Semantic Signatures for Places of Interest
Jiang, Bin University of California, Santa Barbara	What Makes Things Searchable is the Underlying Scale
Jones, Christopher Cardiff University	Toward High Resolution Spatial Search: From Documents to Spatial Facts
MacEachren, Alan M. Pennsylvania State University	Place Reference in Text as a Radial Category: A Challenge to Spatial Search, Retrieval, and Geographical Information Extraction from Documents that Contain References to Places

Matlock, Teenie University of California, Merced	Spatial Search
McDonald, Stephen and Ben Lewis Harvard University	Expanding WorldMap
McKenzie, Grant University of California, Santa Barbara	Spatial Search
Murdock, Vanessa Microsoft	On Language Models for Places from User-Generated Content
Newsam, Shawn University of California, Merced	Visual Spatial Search
Nuernberger, Benjamin et al. University of California, Santa Barbara	Image-Based Spatial Search for Telecollaboration
Parsons, Ed Google	Spatial Search—The Next Evolutionary Step for the Post SDI-Age
Prasad, Sathya Esri	Enabling Flexible Search for ArcGIS Online using Semantic Web Technologies
Purves, Ross University of Zurich	Geographic Information Retrieval: Are we Making Progress?
Schooler, Lael Syracuse University	Limiting Search with Simple Heuristics
Todd, Peter M Indiana Universtiy	From Spatial to Cognitive Search in Humans
Tversky, Barbara Stanford University	Varieties of Spatial Search
Weimer, Kathy Texas A&M University	Gazetteers and the Library Catalog: Infrastructure for Spatial Search
Yuan, May University of Texas at Dallas	Spatial Search Based on Similarity

Appendix C: Word cloud of position papers



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