Route planning using an emergent hierarchical architecture

by Clemente Ignacio Izurieta

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer Science
Montana State University

Abstract:
A cognitive map is a representation of an environment that consists of both nodes and connections. How this hierarchical structure might emerge from a computational standpoint is the focus of this research.

The system builds a cognitive map by traversing routes in an environment. A hierarchical structure emerges when a certain place has been visited often enough to justify its coming to be representative of an entire region.

Places are considered to be connected to one another when there is a traversable route that directly links them. Each time the route is traversed, the cognitive relationship between the two places strengthens. If a place is visited often enough, it will come to symbolize an entire region. Once a region is symbolized, all other places in the region are inhibited, allowing each region to be only symbolized by one place. This process can continue indefinitely, leading to a hierarchy with more and more levels.

We explore some of the properties of such a hierarchical model including how it develops and how it affects the quality of a planned route.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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This thesis is dedicated to my parents Clemente and Georgina Izurieta.

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ABSTRACT

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The system builds a cognitive map by traversing routes in an environment. A hierarchical structure emerges when a certain place has been visited often enough to justify its coming to be representative of an entire region.

Places are considered to be connected to one another when there is a traversable route that directly links them. Each time the route is traversed, the cognitive relationship between the two places strengthens. If a place is visited often enough, it will come to symbolize an entire region. Once a region is symbolized, all other places in the region are inhibited, allowing each region to be only symbolized by one place. This process can continue indefinitely, leading to a hierarchy with more and more levels.

We explore some of the properties of such a hierarchical model including how it develops and how it affects the quality of a planned route.

INTRODUCTION

A cognitive map is an individual's representation of an environment. Figure 1 shows the major steps involved in building a cognitive map. The first component is the physical world, and represents the environment that the system is trying to learn. The second component is a primitive description of the environment, where places in the physical world are represented as nodes in an undirected graph. A connection between two nodes exists if there is a corresponding path between the corresponding places. One paper [**Yeap, Hardley 91**] refers to this second component as a raw map with very little *a priori* cognitive information. Most commonly, other literature [**Hirtle, Jonides 85**] refer to this information as spatial information. Distance and relative locations of places are examples of this type of information. The third component of a cognitive map, also known as a full map [**Yeap, Hardley 91**], contains the non-spatial characteristics of an environment. These characteristics are learned over a period of time, and represent an individual's experience. For example, associating a cluster of places as belonging to a specific region is a process that requires extensive knowledge of an environment. It is this experience that makes cognitive maps unique.

In this system, the raw map is given by a Euclidean map. The Euclidean map is a simple graph representation of a two dimensional environment, where navigation is only possible within a planar surface. Vertical movements are not allowed. Numer-

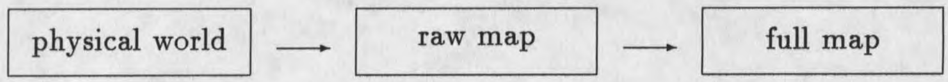

Figure 1: A cognitive map and its components

ous algorithms exist that concentrate on developing raw maps through exploration. For example, [**Lumelsky, Mukhopadhyay, Sun 90**] describe two algorithms for acquiring raw maps of planar terrains with obstacles. This thesis concentrates on attaining the full map. An initial raw map is given as a basis from which experiences will be built, and non-spatial characteristics will evolve as the individual familiarizes himself with the environment.

There are an infinite number of non-spatial attributes that may be recorded in a cognitive map. We are interested in developing non-spatial characteristics that will assist in route planning and environment representation. Evidence suggests that humans remember only the major landmarks when planning routes, and fill in the rest of the route as they navigate through the environment. Numerous experiments [**Allen, Kirasic 85**] have been designed to see how route knowledge on macrospatial environments is retained. Studies on macrospatial environments are concerned with the development of knowledge in large scale environments. In their findings they suggest that "individuals tend to organize their experience into distinct segments." They show how this segmentation affects an individual's proximity judgements, and distance estimates. Segmentation of routes also suggests that information might be stored in some sort of hierarchical structure. A series of studies [**Hirtle, Jonides 85**] experiment with this idea and show how it affects human orientation judgement. They suggest that landmarks that are close in proximity tend to be associated with a particular region. Numerous psychological experiments have been carried out in this subject, for example, an experiment where "most subjects judge Reno, Nevada to be northeast of San Diego, California, even though it is actually northwest" [**Stevens, Coupe 78**] shows that individuals use some kind of "superordinate relationship" such as a hierarchy of landmarks to make their decision.

In the system introduced in this thesis (Bushman), a hierarchical structure is used to store route information. The hierarchical structure is dynamic in the sense that it *grows* as the individual navigates through the environment. As new associations of places are formed, new levels in the hierarchy emerge. The hierarchy becomes a kind of database that stores route knowledge in a global sense, and most of this information is used when planning a route to some destination. Figure 2 shows a hierarchical structure consisting of three levels.

In this figure, we see an example of a hierarchy where the physical world is made up of some dark locations, and some light locations. The dark locations represent regions in the physical world. Two such regions are depicted. A location emerges to become a landmark, when it has been visited often enough to justify its coming to be representative of a region. The two vectors depicted originate from such locations. The squares at the end of the vectors represent the emerged higher level landmarks,

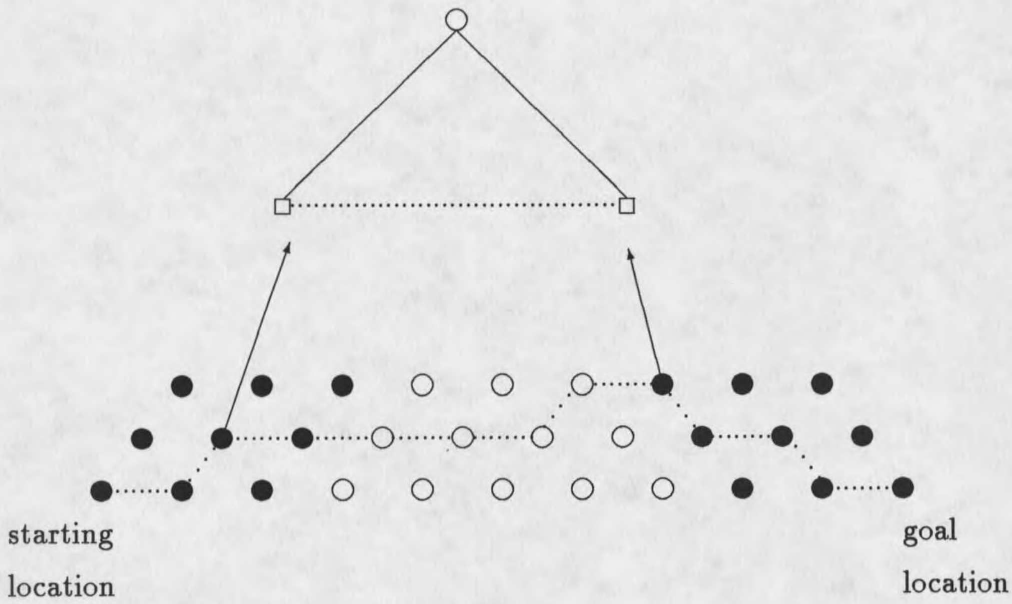

Figure 2: Hierarchical structure used for planning routes

with the dotted line representing a logical connection between them. Connections of this type are needed to maintain logical relationships between landmarks. The circle represents yet another region, this time however, it represents the region of squares. To plan a route from a starting location to some goal, the first region associates itself with a higher landmark in the hierarchy. It associates itself by finding a location in the current level that has been traversed enough times to become a representative landmark of the region. The same is done by the other region. A route is now planned at this higher level. Once this process is finished, we drop a level in the hierarchy and plan a route from the start location to the location that represents the current region at the next level, then we plan to the location that represents the region where the goal location is located, and finally we plan to the goal location.

The following chapters provide a detailed discussion of how the system operates, and several tests on the robustness of the system are performed. Future research will be discussed that shows what areas of this system need to be pursued in the future.

A REVIEW OF RELATED WORK

Before any planning can take place, a representation of the world is essential. There are numerous ways of providing a representation of the world, such as, undirected graphs, hierarchies, self organizing neural networks, and even rules in a production system. Once a representation is chosen, the selection of a method that best utilizes the representation needs to be selected. This method should have the ability to search the knowledge in the representation in such a way that goals are accomplished in an efficient manner. The following section gives a partial overview of some approaches to world representation and route planning.

Kuipers

One system [**Kuipers 78**] attacks the problem of modelling human routes in terms of a production system. The knowledge about routes is stored as two types of associative links:

- Link V->A means that when the current view is V, then action A is taken to follow the route.

- Link (V,A)->V' means that if the action A is taken in the context of view V, the result will be view V'.

If a route consists of links of both types, then the entire route can be reproduced in the absence of the environment, however, if links of type V->A are the only ones present, the route can only be traversed physically. This is due to the fact that the environment itself contains links of the type (V,A)->V'.

The method used by Kuipers is not without its counterpart in biology. Studies about orientation techniques used by honey bees [**Whener, Raber 79**] show that reconstruction of paths is carried out using sunlight as a reference. Most importantly however, bees are assumed to memorize two dimensional photographs of the environment which they use together with the sunlight cues to reconstruct routes.

RUR

This system [**Nehmzow, Smithers 90**] was developed to explore map building abilities using self organizing neural networks integrated in RURs (Really Useful Robots). Basically, the robot is placed within some environment, and allowed to explore the environment over a period of time. During this time the robot navigates the same map a number of times. Each time that the robot encounters a corner, an input vector describing this corner is given to the neural network. After a number of trials in the environment, the robot has adjusted the weights of the neural network in such a way that it is now able to recognize different areas of the map. When this state is reached, it is said to have an internal representation of the environment, a cognitive map.

This mechanism can also be compared to the recognition abilities that bees use to navigate. As described in one system [**Kuipers 78**], bees use two dimensional pictures of the environment to help aid navigation and reconstruction of routes. A method similar to a self organizing neural network could be being used to actually recognize this two dimensional picture. Various studies [**Gould 88**] support this thread of investigation. One such study states that "bees compare stored retinal patterns to the current retinal pattern to calculate a flight direction vector."

Toto

Toto is a robot equipped with sonar sensors and a compass. The robot [**Mataric 90**] is based on the subsumption architecture by Rodney Brooks. There are three layers of competence that are used by Toto, however, this overview will only concentrate on the map building layer. Competence layers act independently to carry out specific tasks needed by the robot. The internal representation of the environment is achieved using a network of locations representative of some physical world. Each node in the network has the ability to send and receive signals from adjacent nodes. Building a cognitive map is achieved through exploration of the environment, and assigning a new node to newly encountered locations. Finding a route to a given goal is achieved through a process called *spreading activation* and works by having the goal node in the network send a signal to adjacent nodes, which in turn spread the signal in the same manner as the goal node. When the signal reaches the node where the robot is located, all that the robot needs to do, is follow the signal from the direction it arrived.

The distributed network model of a cognitive map [**Mataric 90**] is representative of the organization of the rat's hippocampus, where each node is representative of a *place cell*. Place cells are said to fire when a rat is placed in a known location. A more biologically plausible situation is to represent a landmark with a set of nodes rather than a single node. It is very likely that places are represented by more than a single place cell in the rat's hippocampus.

Summary

The research surveyed in this section represents a small sample of a vast research area. A common thread running throughout the diverse research surveyed is a relationship with biology. In the following chapters, a detailed description of *Bushman* will be provided, and its hierarchical representation together with its planning algorithm will be studied.

THE HIERARCHY AND ALGORITHM

Bushman consists of two major components. The first component is an internal knowledge representation of a two dimensional environment. This knowledge includes the spatial and non-spatial information described in the introduction. The second component is a recursive algorithm that uses the internal knowledge representation to plan routes.

The Physical World

The physical world is represented as a graph, and consists of both nodes and connections. Each node represents a location and each edge represents a path between two locations. Each location in the graph contains the following:

- A name
- An activation threshold
- Map coordinates
- A status level
- A list of adjoining neighbours

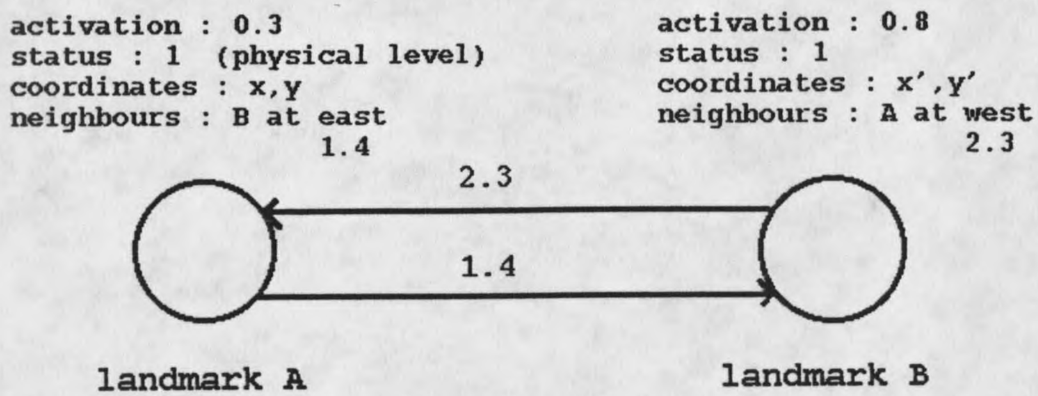

Figure 3: Two node physical world

- A corresponding synaptic strength and orientation for each adjoining neighbour.

There are other bookkeeping fields that are not directly relevant to the mechanics of the algorithm. Figure 3 shows an example of a two node physical world.

An important observation shows that connections between any two adjacent locations are bidirectional. Bidirectionality however, does not imply reflection. This means that a planned route from A to B may not be the same as the route planned from B to A. One author [**Kuipers 78**] writes "Szeminska (1960) observed that young children are frequently able to follow a route correctly from beginning to end, but are unable to travel the same route in reverse, or start it in the middle."

The Emergence Of Hierarchies

The raw map forms the foundation upon which the full map will develop. The system will build a cognitive map by traversing routes in the physical world. A route is considered to be a path of successive edges between any two locations. A hierarchical structure will emerge when a certain location has been visited often enough to increase its activation value beyond some threshold. The activation value is otherwise known as the saliency of a location, and measures its importance with respect to other locations. Figure 4 shows a physical world consisting of five locations and their respective activation values. The activation value of the black location has surpassed that of the threshold, and has therefore promoted the location to become representative of an entire region. The size of a region is variable and can be preset by the user. Any locations within this region are inhibited from rising in importance, and hence rising in the hierarchy. This avoids having every location rise in the hierarchy.

In time, other locations will rise in importance and will be promoted to a new level. When a location has its importance raised, new connections will be made to other nodes at this same level of importance. The system looks for landmarks that are close in proximity to the newly promoted location (now a landmark), and creates a bidirectional connection from the new landmark to all the landmarks within a given radius at the new level. If no landmarks appear to be within the specified radius, then the newly promoted location looks for the closest possible landmark