

Chapter 2

Landmarks: A Thought Experiment

Abstract A thought experiment illustrates the fundamental role of landmarks for spatial abilities such as memory, orientation and wayfinding, and especially for human communication about space. We take a constructive approach, starting from a void environment and adding experiences supporting spatial abilities.

2.1 Experiment

In 1984 the neuroscientist Braitenberg presented a fascinating thought experiment by constructing increasingly complex ‘vehicles’ from a small set of primitive abilities [3]. Already with a few of these abilities combined the ‘vehicles’ showed a complex behavior hard to predict. Braitenberg introduced his experiment with the words ([3], p. 2):

We will talk only about machines with very simple internal structures, too simple in fact to be interesting from the point of view of mechanical or electrical engineering. Interest arises, rather, when we look at these machines or vehicles as if they were animals in a natural environment. We will be tempted, then, to use psychological language in describing their behavior. And yet we know very well that there is nothing in these vehicles that we have not put in ourselves.

Braitenberg explained a complex system—such as the brain, or human behavior controlled by the brain—by demonstrating that a combination of a few simple modules already develops complex behavior. A similar approach of constructing complex systems from simple mechanisms was also taken by Couclelis [5] to explain self-organization of urban dynamics, or by Both et al. [2] to speculate how complex spatiotemporal behavior arises from spatiotemporal knowledge.

Let us devise an experiment in a similar vein. We pose a few simple modules for human orientation and wayfinding in an environment in order to see how the central role of landmark experiences arises quickly.

2.1.1 *The Void*

Imagine an environment with no structure at all, like in Genesis 1.2: “The earth was without form, and void; and darkness was upon the face of the deep”. The only structure given is a flat infinite surface orthogonal to gravity. Walkers are presented with a monochrome empty plane up to the horizon, under a white sky of diffuse light. There is no further structure in this environment, and no hint for direction other than the vertical axis imposed by gravity. There is not even shadow supporting a sense of direction. All what the walkers experience in this environment is their own locomotion, and thus path integration. Their body will tell them from which location they originated. Therefore they can always point in the direction of this location and guess the covered distance, a mental ability called homing [14]. In their desire to establish and maintain orientation in this empty environment the only location to relate to is this point of origin. Let us call it *home*. Home is the only place there is. Thus home becomes a reference point for the exploration of the environment: A landmark.

If this environment would have force fields that differ by location then sensing the force differentials could support the sense of direction. For example, if walkers would be equipped with a magnetic sense, or a compass as an external device, their mental effort to maintain their sense of direction would be supported considerably [21]. Similarly if the plane would be tilted towards gravity their sense of gravity would add observations to path integration.

2.1.2 *Adding a Landmark*

Now imagine that a walker, after roaming around to discover the environment, stumbles upon a coin on the ground. This walker, picking up the coin, might feel lucky. At last she has an experience in an otherwise uneventful environment. This experience is linked to a location. She will remember the event, and for a while also its location: Another landmark.

When she returns home she wants to report to her friends where she has found the coin. How can she do this given that there are no external cues in the environment? All she can refer to are directions and distances related to her body. She might say: “Over there [pointing], perhaps 20 steps from here”, the direction physically linking to her body, and the distance in a quantity relating to an internalized measure that can be realized by walking. The reproducibility of measures proportional to the body or body mechanics will help her even in communicating with friends, assuming they have a body like her. Scheider et al. also concerned about grounding human experiences of space, wrote ([18], p. 76):

Humans perceive length and direction of steps, because (in a literal sense) they are able to repeat steps of equal length and of equal direction. And thereby, we assume, they are able to observe and measure lengths of arbitrary things in this environment.

They then went on to develop a theory of steps between foci of attention. In our thought experiment we stick with the embodied experience, memory and communication of the walker (coming back to formal models in Chap. 4). In this regard it is interesting to see how instead of words the walker used pointing to communicate the direction. Finding words of similar accuracy in this environment would have been quite difficult. The distance, however, was expressed in a quantitative manner. A qualitative description might have come to mind more easily: “Over there [pointing], not too far from here”. The qualitative description can be generated with less cognitive effort (we will come back to ‘quality over quantity’ in Sect. 3.3.2.1), but its realization might be more uncertain. In addition, the interpretation of a qualitative term is context-dependent; *not too far* does mean different things when talking about a car ride or an exploration of the immediate neighborhood, and in this empty environment there is not much shared experience between the walker and her friends that would establish context.

For her friends, the realization of her place descriptions is subject to uncertainty. While an instruction “20 steps” may produce less uncertainty than “not too far”, it also takes more cognitive effort to realize by requiring counting. And since the coin was picked up by the walker, the landmark experience of her friends is only a mediated one.

Human bodies vary. For example, using foot lengths or step lengths as measures depends on an individual’s body and can be reproduced by another person only with some uncertainty. Hence, when quantities need to be accurate some agreement is required on an absolute measure, which is a measure independent from an individual body. Most standardized unit measures are anthropomorphic, based either on average body dimensions (e.g., the length of a foot), or on human body movement (e.g., the length of a step). Even the *meter*, our today’s standard unit according to the International System of Units (*SI*, from *Système International d’Unités*), was defined as a breakdown of the length of a great circle of the Earth to a unit in some relation to the scale of the human body. In order to be reproducible by everybody, an absolute distance measure requires from an individual learning their individual body properties (e.g., step length) compared to the standard. With other words, absolute measures require an additional layer of cognitive effort in realization.

Now, whether quantitative or qualitative, the tuple of distance and direction is well-known in geometry as polar coordinates. Coordinates are only meaningful within a given reference system, and in the given scenario the coordinates can only be embedded either in the egocentric reference system of the body of the speaker or of the recipient [11]. It is up to the speaker to convey the intended interpretation. For example, the speaker could have said: “Straight, not too far”.

This expression could refer to the direction in front of herself (“put yourself in my position; straight in front of me”), or could have referred to the direction in front of the friend (“from your position walk straight”). For the prior interpretation, the recipient must transform the instruction by a mental rotation from the orientation of the speaker to their own orientation. For the latter interpretation, the speaker must do the mental rotation before speaking. Both is practical only when speaker and recipient are meeting face-to-face. If they are communicating over a distance (e.g., telephone) or asynchronously (e.g., email) the communication of body-pose related directions requires links to external cues. Since they do not exist in this environment such a communication is simply impossible [10]. Pointing, however, conveys the intended interpretation because it happens within the shared space [7].

What applies to the communication of direction—the ambiguity of the reference system, and the need for a mental transformation between reference systems either by the speaker or the recipient—applies also to the communication of distance. If the distance from the speaker is “about 20 steps” this information may need to be updated by the recipient according to their different positions and step sizes, and if the speaker actually means “about 20 steps in front of you” this interpretation needs to be conveyed as well. These mental transformations—rotations and translations—require spatial skills people have only to varying degrees [1, 19].

Stripped of any external cues within the environment, the walker will find it hard to describe accurately the location where she found the coin. The more time passes, or the more other walks she will have made since then, the less will she be able to reenact the locomotion experience. Constant updating of multiple vectors (home and all discoveries made over time) will become an overload, and the walker will give up maintaining those vectors felt no longer to be essential (last the homing vector). She may not necessarily forget the event itself, but she may forfeit her ability to describe its location. For a while though, the event provided a second landmark for the walker. In the real world we have similar experiences. “Let’s meet at the café where we have met first” works in communication because this café has attached emotional value, is remembered for the meeting and for its location, and thus the location is describable and can be found again.

2.1.3 *Adding Structure*

From here on our thought experiment splits for a while into three parallel streams. One continues with constructing a memorable space (Sect. 2.1.3.1), another introduces a global frame of reference (Sect. 2.1.3.2), and a third one defines an arbitrary frame of reference (Sect. 2.1.3.3). Each of them ends up with a network structuring the environment, although motivated by different principles. The lines will be reunited in Sect. 2.1.3.4.

2.1.3.1 Adding More Landmarks

Let us assume the walker decides to mark the location where she found the coin with some chalk on the ground. She also draws a line on the ground from that location to home. Home is another mark on the ground. These externalized landmarks can now be found even with fading memories of path integration. The experience of walking can be repeated, can be communicated easier to others, and can be shared by others.

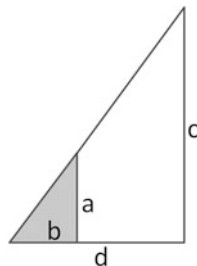
Further landmark experiences in the environment can be added over time, and connected to the existing ones. What forms over time is a travel network between landmarks. The intersections in this network were originally destinations, or locations of particular (shared) memories or stories. But over time also the edges in the network get some prominence, since they are commonly experienced by some embodied locomotion. As the dependent elements (e.g., “the route from home to the place where we have found the coin”) their prominence may be lower, but we will argue later in the book that they will also share some landmarkness. For example, the walker and her friends can give names to edges (or sequences of edges in this regard). If over time the stories of the original landmark experiences fade away the prominence of the named edges may even get stronger (e.g., “the coin route”).

Whatever elements are the primary anchors, either the connected landmark locations or the dual view of the edges between landmarks, this network enables for spatial tasks such as orientation and wayfinding. Using landmark orientation would be maintained either with local landmarks (“I am at the location where the coin was found”) or with global landmarks (“I am three intersections from home”), and route planning would be about an appropriate sequence of landmarks (e.g., “From home to the location where the coin was found, and then right”). Using edge orientation would be maintained also either locally (“I am on Coin Route”) or globally (“Coin Route must be in this direction”), and route planning would be about an appropriate sequence of edges (e.g., “Point Route, then turn right into Serendipity Street”).

2.1.3.2 Adding Directed Light

Alternatively, let us change the settings of the experiment slightly. Instead of diffuse light imagine there is a point-like light source, mounted several times above body height. Call it *the sun* although it will not move in this experiment. This sun can be observed from any location, and since it is the only marked point in the environment—a singularity in an otherwise homogeneous empty space—it will attract attention from walkers. It also provides a reference direction for orientation and communication. Instead of using solely their locomotion-based orientation, walkers can now refer to the sun: “Walk towards the sun”. Even on the ground is now a singular location where the body throws no shadow, which is where the sun is in zenith. This point can be found by any walker. It is an embodied experience but also a characteristic of the environment, and thus independent from previous locomotion. Therefore it can be used as a common, or shared reference point. Everybody can find it with no further instructions about its distance or direction.

Fig. 2.1 Similarity of triangles between body height (a), shadow length (b), height of the light source (c), and distance from the pole (d, to the peak of the shadow)



With respect to this reference point distances can be estimated: “Closer to the sun” means a location where the walker has a shorter shadow (an embodied experience), “near the sun” may have some context-dependent meaning related to shadow length, and even quantities can be given, such as “within 10 step lengths from the pole under the sun”.

Since in our thought experiment the height of the sun is related to human body dimensions, and constant, the walker and her friends could develop over time also a sense of distance from the pole by observing the angle of the sun above the horizon, or the length of their body’s shadow, instead of estimating steps from path integration. With a constant height of the sun c and body height a , the shadow length b is proportional to the current distance from the pole $d - b$ by the similarity of triangles (Fig. 2.1):

$$\frac{a}{b} = \frac{c}{d}$$

Moreover, by applying projective geometry any walker can (re-)produce lateral circles around the pole. In a salient distance from the pole (say, every 10 m) turning orthogonally to their shadows they keep walking with keeping the sun constantly to their right until they reach their starting point. These lines, imaginary or also drawn by chalk, can play a role in the mental conceptualization of the space: “The coin was above/below the lateral circle at 50 steps” may sound a bit arbitrary as an example, but consider the decree by Pope Alexander VI that divided the world between Spain and Portugal along a meridian of 100 leagues west of the Cape Verde Islands. This line got a historic meaning, and had landmark character.

However, in order to relieve human memory from relying on tracked locomotion, locations should be specified as points in space. We get there by adding only one additional element to our experiment. Let us assume the walker, after finding the coin, moves back straight to the pole (towards the light) and marks the direction to

Fig. 2.2 The Greenwich meridian: an arbitrary choice to anchor a geographic coordinate system (CC-BY-SA 3.0 Rodney Brooks)



the location of the discovery by chalk on the ground. By doing so she defines a prime meridian (Fig. 2.2). Let us call the direction of the prime meridian *North*. With a marked direction and the memory for the distance the walker has now a reproducible characterization of the location of the discovery, one that does not change and is not dependent on her actual pose or location. Compared to path integration, requiring constant updating of all related locations, this is quite a relief for her memory. If she wants to find the location again she only has to come back to the pole (a landmark), find the prime meridian (another landmark), and memorize the distance. If she wants to tell friends she can now text: “Go to the pole, find the prime meridian, and walk about 20 steps”, and neither of them has to be at the pole at the time of communication. Furthermore, future other discoveries can be linked to the pole and prime meridian as well. The pole becomes the datum point of a global reference coordinate system.

So, similarly to the world constructed from landmark experiences alone (Sect. 2.1.3.1), a global reference coordinate system relieves from constantly updating internal representations, and takes over to anchor other locations. Additionally we have gained a (polar) network structure by marking salient locations with reference to the datum—the pole and the prime meridian. The city of Karlsruhe in Germany, for example, shows such a radial network of lateral circles and meridians, laid out from the palace in the center (Fig. 2.3). Alternatively, the walker could lay out a rectangular network by constructing parallels to the prime meridian and then perpendiculars to the meridian. A rectangular network has the advantage of allowing constant block sizes, where the radial network has constantly increasing blocks with the distance from the pole. A rectangular grid is a street network pattern chosen in many European settlements in the new colonies of the eighteenth and nineteenth century, such as North America and Australia.

2.1.3.4 Networks Structuring an Environment

We are now ready to reunite the three alternative lines of our thought experiment. Whatever network the walker chooses, the result is a structure of nodes (say, street intersections) and edges between nodes (say, street segments between intersections). Such a structure is a graph [4, 9, 15, 22]. This graph, since it was drawn by the walker on the ground, is also planar (each intersection of edges is a node) and embedded (each node is at a particular location on the plane).

Each network structures the environment independent from prior landmark experiences. It has distinguished locations, the intersections, that are easy to perceive with the body senses as locations of choice. They are memorable, and hence landmarks by themselves. Since the walker could draw only a network of limited extent the individual intersections are countable and finite. Instead of polar coordinates within the polar reference system locations can now be described using this discrete network, e.g., “at the corner of”. Distances can now be measured in numbers of intersections. Directions are discrete as well. In the radial and the rectangular network only right angles exist, and even in the free-form street networks intersections offer a very limited number of possible directions to take. In graph theory, this property is characterized by the *degree* of nodes: The degree of a node is the number of its incident edges. Radial and grid network have only nodes of degree 4, except the pole in the radial network and the outer boundary of the networks. Free-form street networks can also have nodes of degree 1 (dead-ends), degree 3 (e.g., T-intersections) and degrees higher than 4 (more complex intersections). However, due to physical space constraints this number cannot be arbitrarily large. From a cognitive perspective the limited number of directions is again a relief. The walker does no longer need to control constantly direction and to integrate steps. Instead, the walker only counts the passed intersections and memorizes discrete turn choices. These typically low counts are not stretching numerical cognition and short term memory [6, 13].

Networks may appear relatively plain, but then there are also individual differences coming out of node degrees or node (or edge) centrality. For example, the pole in a radial network has a node degree standing out in the otherwise regular structure, and it is also the node of highest betweenness centrality in the network—betweenness centrality of a node in a graph is a measure of how many shortest paths a node is in [8]. The latter means that statistically it will be experienced more often by walkers than other nodes. These reasons add to the pole’s experiential features. The pole is a stronger landmark than the other intersections, and due to its uniqueness in this respect it is a *global* landmark. One function of a global landmark is supporting global orientation and wayfinding. For example, even if a walker somewhere in the radial network feels temporarily disoriented, some simple heuristics will lead her back to the pole. She will follow the next meridian, i.e., the straight streets towards the sun, and will reach the pole. In other network forms local variations may produce more subtle differences between nodes, but centers or bottlenecks will stand out as well. A regular node, however, is a *local* landmark. It helps locating events and referencing to these events as local anchor points.

For example, if the coin would have been found along an edge, not at a node, any of the following would be a natural reference: “Near corner West fourth St and Prime Avenue”, or “In West fourth St, 30 steps from Prime Avenue”, the latter implying an intersection of the two streets.

2.1.4 *Filling with Further Landmarks*

Now let us imagine the cells enclosed by network edges and nodes are filled with white blocks, larger than the human body. These blocks limit the sight of walkers. Since they are plain white without further texture or structure they are nearly indistinguishable for the human senses. There is no particular bodily experience attached to the encounter of any individual block except the shape of the cell they occupy.

These blocks get more importance in our experiment if we give them individual faces or meanings. Individual blocks can get attached a special shape, or a special color. A block can be labelled “supermarket”, and another one “café”. These blocks stand out from the other ones that were left unchanged plain white. They provide a special experience for passersby. Walkers will memorize these experiences, and attach them to the locations where they make these experiences. As long as these labelled objects are globally unique and only few they can have global landmark characteristics. “In the direction of the supermarket” provides global orientation if everybody knows the supermarket. They can also take the function of local landmarks. People can refer to it when describing local events (“in front of the supermarket”, “three blocks from the supermarket”), either trusting that the recipient has made the encounter with the supermarket before already, or will easily identify it when passing by. “At the supermarket” is an even more efficient description than “at the third intersection” because it does require only one object recognition task, and no counting.

However, landmarks do not have to be globally unique. There might be a second supermarket in this environment, perhaps even of the same brand, as it happens out there in any real city. The two supermarkets are still differentiable from the rest of the environment, but an instruction such as “At the supermarket” must be considered ambiguous now. There are three common cognitive mechanisms that are used for disambiguation of local landmarks in a communication context:

1. *Nearness*: “At the supermarket” is disambiguated by choosing the nearest individual as a default. Behind this cognitive heuristics is also embodied experience since the cost of interaction with the environment is inversely proportional to the cost of travel: the nearest supermarket is the easiest one to reach. The argument is additionally supported by the first law of geography as stated by Tobler: “Everything is related to everything else, but near things are more related than distant things” ([20], p. 236).

2. *Order*: “Go straight and at the supermarket turn left” cannot be solved on the assumption that this *next* supermarket in a particular direction is also the nearest one. Instead a principle of order comes into play. The next supermarket is the first encountered in a particular search. By the same ordering principle one could equally well say: “At the second supermarket turn left”.
3. *Hierarchical priming*: While “at the supermarket” is ambiguous, “at the supermarket on Prime Avenue” is less likely ambiguous (depending on whether the street name is a differentiator). This hierarchical localization [16,17] works recursively if needed, i.e., in cases where Prime Avenue either is not unambiguous or not prominent enough. “At the supermarket on Prime Avenue, in the Southern sector [of the environment]” is adding in this way. There is strong evidence that spatial mental representations are hierarchically organized.

Hierarchical priming happens also through salience hierarchies of landmarks. For example, a hierarchical description (or thought) “I found the coin in the entrance of the supermarket, not far from the ATM” refers to the supermarket as a global landmark, and then specializes further by another reference to a local landmark, an ATM. Here the hierarchical priming is required for disambiguation between the many ATMs in an environment. This way, hierarchies help to break down large environments into manageable regions of influence. Any object or event in the environment can be related to landmarks in a variety of ways, qualitatively and quantitatively. Besides of something being “near the supermarket” (distance, defining the region of influence), its location can also be characterized as “on the way from supermarket to home” (orientation), as “on the right when travelling from supermarket to home” (direction), as “between the supermarket and home” (projection), or as “in the quarter of the supermarket” (topology). Quantitative characterizations are possible as well, such as “30 m from the supermarket”. Also the prominence of a landmark can prime the memory for a particular street segment, as in “I found a coin in the street where the supermarket is”.

2.2 Summary

A thought experiment has illustrated the fundamental role of landmarks for structuring mental representations of an environment. In the constructive approach of the experiment we have assumed an environment that provides salient experiences linked to locations, and expected that these experiences form anchor points in memory, and also configurations that allow relative orientation. We have in particular learned that landmark configurations are sufficient for spatial cognitive tasks such as orientation and wayfinding. The existence of a global frame of reference, which is essential in any technical system, from spatial information systems to robots, is not essential for human spatial problem solving as long as the environment provides configurations of landmarks allowing relative orientation. We have also learned that experiences at particular locations form landmarks, and these experiences can also be experiences of the structure (nodes) or dimensions (edges) of the structure of an environment.

The fact that our environment resembled an urban environment does not matter. The same insights about landmarks could have been made in a process introducing landmarks in a landscape. Spatial cognition certainly developed in natural environments, but its mechanisms apply equally in human-made environments.

Landmarks' primary role appears to be structuring a mental representation of an environment by forming anchors for relational links. Verbalized, these anchors and their links appear to convert into relational descriptions. Evidence for this assumption will be presented in the next chapter. Without landmarks both tasks, forming a mental representation of an environment and, correspondingly, being able to communicate about locations in the environment, appear to be significantly more complex, relying on locomotion and path integration only.

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