

THE CONTRIBUTION OF 3D ENVIRONMENTS TO CONCEPTUAL UNDERSTANDING

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Abstract

This paper explores the potential learning benefits of 3D Learning Environments (3DLEs). It presents definitions of key terms and analyses the learner-computer interactions facilitated by 3DLEs, in order to identify the unique characteristics of such environments. It is argued that the most important potential contribution of 3DLEs to conceptual understanding is through facilitation of spatial knowledge development. The effectiveness of 3DLEs for spatial learning is discussed, drawing on literature from a range of disciplines. Aspects of a research agenda are identified including exploration of the characteristics of 3DLEs that are most important for spatial learning along with issues in designing appropriate learning tasks.

Keywords

3D environments, virtual environments, spatial perception, spatial learning

Introduction

3D technologies have revolutionised computer games to the extent that virtually all new games are based upon 3D graphics. Some might claim that it is only a matter of time before 3D environments become the norm for other types of software, such as business systems, desktop user interfaces and online learning resources. On the surface it would appear that 3D environments have great potential in educational contexts as they provide the possibility of rich learner engagement together with the ability to explore, construct and manipulate virtual objects, structures and metaphorical representations of ideas. This paper examines the pedagogical benefits of 3D environments by consolidating findings from cognitive psychology, visual cognition, and educational psychology. A particular focus within the paper is on the way 3D environments can facilitate learning of complex conceptual relationships.

3D Learning Environments

The term 3D Environments used in the title of this paper was chosen in preference to the term Virtual Environments, due to the wide differences in the way the latter term is now used. The definition used by Wann and Mon-Williams (1996) clearly describes the main aspects of a 3D environment, stating that such an environment “capitalizes upon natural aspects of human perception by extending visual information in three spatial dimensions and may supplement this information with other stimuli and temporal changes” and that “a virtual environment enables the user to interact with the displayed data” (p.833). Three-dimensionality, smooth temporal changes and interactivity are the most important features that distinguish 3D learning environments from other types of virtual learning environments.

Our primary focus is 3D environments that can be explored using standard PC hardware, commonly termed ‘desktop virtual environments’, as distinct from those that require specialised hardware such as

head-mounted displays, which are commonly termed ‘immersive virtual environments’. Recent advances in the capabilities of standard desktop computers allow for richly detailed 3D environments to be delivered at realistic frame rates and with very high response rates (Kelty, Beckett and Zalcman, 1999). Aside from the accessibility advantages of desktop environments, there are also significant usability advantages. For example, Robertson, Card and MacKinlay (1993) argue that desktop 3D environments can be easier to use than immersive environments because people are already familiar with controlling the desktop computer, and such environments do not subject the user to the physical and psychological stress often associated with immersive environments. Additionally, the paper focuses on single-user 3D environments. Although there is significant potential for collaborative learning through multi-user environments, these environments are outside of the scope of the analysis presented in this paper.

Distinguishing Characteristics of 3D Learning Environments

3D environments have a unique set of characteristics from a pedagogical point of view. Hedberg and Alexander (1994), identify the features of virtual environments that make them distinct from interactive multimedia; highlighting three aspects of virtual environments through which such environments have “the potential to offer a superior learning experience” (p.218), increased *immersion*, increased *fidelity* and a higher level of *active learner participation*. Whitelock, Brna and Holland (1996) propose a theoretical framework encompassing the relationship between virtual environments and conceptual learning. Their framework consists of three dimensions, *representational fidelity*, *immediacy of control* and *presence*. There is a degree of agreement between Hedberg and Alexander’s ideas and Whitelock et al’s model. Fidelity appears as a factor in both, immersion and presence are similar ideas, and Whitelock et al’s immediacy of control equates very closely to Hedberg and Alexander’s active learner participation.

The degree of realism, or fidelity and the mechanisms for learner control also figure in the model proposed by Thurman and Mattoon (1994). Their model contains three dimensions: *verity*, which is the degree of realism on a scale from physical to abstract; *integration*, which is the degree of human integration into the environment ranging from batch processing to total inclusion, and *interface*, which ranges from natural to artificial. McLellan (1996) emphasises the importance of immersion, suggesting that “the sense of presence or immersion is a critical feature distinguishing virtual reality from other types of computer applications” (p.457).

It could be argued that the sense of presence or immersion in a 3D environment occurs as a consequence of the fidelity of representation and the high degree of interaction or user control, rather than being a unique attribute of the environment. The dependency of immersion on other aspects of the environment is noted by Hedberg and Alexander when they suggest that “the interaction of representational fidelity with sensory, conceptual and motivational immersion needs to be examined to determine the complexity of sensory input necessary to establish the learning outcome.”

The two most important visual factors in the fidelity of a 3D environment are the degree of realism provided by the rendered 3D images, and the degree of realism provided by temporal changes to these images. The display of objects using realistic perspective and occlusion, and realistic texture and lighting calculations allows for a degree of realism that can approach photographic quality if the 3D model is defined with sufficient detail. However, even when the images do not approach photographic quality, with sufficient frame rates (15 frames per second is normally considered the minimum), the image changes that reflect the viewer’s motion or the motion of objects, can appear smooth enough to provide a very high degree of realism. Another aspect of the fidelity of the representation is the degree to which objects behave in a realistic way or in a way consistent with the ideas being modelled.

The two aspects of learner control, or learner activity, that are unique to 3D environments are the ability to change the view position or direction, giving the impression of smooth movement through the environment, and the ability to pick up, examine and manipulate objects within the virtual environment. Additionally, in 3D environments that involve objects moving autonomously, simulating real-world or abstract properties, the learner can be given control over the parameters of the simulation or the speed at which the simulation proceeds.

Taking the view that immersion is a consequence of other factors, rather than being a unique characteristic, and summarising the factors that contribute to fidelity and learner control, Table 1 lists the

learner-computer interactions facilitated by 3D learning environments that distinguishes such environments from other interactive learning resources.

Category	Interaction
Fidelity	Realistic display, including 3D perspective, lighting and occlusion
	Smooth update of views showing viewer motion or panning
	Smooth display of object motion
	Consistent modelling of object behaviour
Learner activity	Control over view position and direction
	Object manipulation
	Control over object model and simulation parameters

Table 1. Unique Learner-Computer Interactions Facilitated by 3D Learning Environments

Contributions of 3D Environments to Learning

The exploration of 3D environments modelled on places that cannot be visited, such as historical cities, outer space or the ocean floor, is probably the most often discussed application of such environments in learning. For example Alberti, Marini and Trapani (1998) describe an environment modelled on a historical theatre in Italy. Similar is the exploration of microscopic objects, such as molecular structures (Tsernoglou, Petsko, McQueen & Hermans, 1977 cited in Wann & Mon-Williams, 1996).

Another commonly discussed application of 3D environments is skill mastery, especially in situations where the skills being learned are very expensive or very dangerous to practice. For example, such environments have been used to train nuclear power plant workers (Akiyoshi, Miwa & Nishida, 1996 cited in Winn and Jackson, 1999) and to train astronauts in repair of a space telescope (Psotka, 1994 cited in Moore, 1995).

Ruzic (1999) emphasises the situated nature of learning in virtual environments, and consequently the potential for transfer to similar real environments, suggesting that “the advantages of VR-based teleteaching are individualised, interactive and realistic learning that makes virtual reality a tool for apprenticeship training, providing a unique opportunity for situated learning.” (p.188). McLellan (1996) also notes the potential for 3D environments to situate learning, drawing on Brown, Collins and Duguid’s theory of situated cognition (1989).

Another potential learning benefit of 3D environments is that such environments can be intrinsically motivating. The high degree of fidelity and the natural interface of 3D environments can allow users of such environments to experience a feeling of *flow*, as described by Csikszentmihalyi (1990). According to Csikszentmihalyi some activities can be so engaging that our mental focus is shifted away from our surroundings and from the day-to-day stresses in our lives, allowing us to focus entirely on the task.

Sweller (1998) discusses the importance of reducing the cognitive load in presenting instructional information, by minimising the demands on working memory. One effect discussed is termed the *split attention effect*, which occurs when the learner has to refer to two or more distinct information representations, such as a picture and a separate caption, resulting in an increased cognitive load. Sweller’s research suggests that if the various sources of information can instead be integrated the demands on working memory can be reduced and consequently the cognitive load is reduced. The integration of graphical and textual information, possibly supported by audio, within a 3D environment is consistent with these ideas.

Some learning situations require a complex array of learning resources to be accessible to the student. The provision of an interface that allows easy navigation through the information, while maintaining a sense for the overall structure of the resources and the connections between ideas, is problematic. Sometimes a 3D model of the information provides for a clearer understanding and a corresponding 3D interface provides for easier navigation. The use of a navigation metaphor has been found to be effective in many applications (for example the desktop metaphor used ubiquitously on personal computers), and the extension of such metaphors to 3D has potential benefits. For example Robertson et al (2000) describe the use of a 3D interface for task management on a PC.

One of the most important potential learning benefits of 3D environments is in developing an understanding of the complex systems we encounter in the world, such as the environmental ecosystem, physical and electrostatic forces, or the intricate workings of a machine. 3D environments that allow the learner not only to view the system from any viewpoint, but to manipulate the objects and modify the simulation parameters, have the potential to facilitate a much greater level of understanding of the modelled concepts than conventional learning strategies. For example, in the discipline of physics, students are expected to understand how objects will respond to forces. By exploring an environment that allows for specific forces to be applied to objects and for the resultant object behaviours to be observed and measured, a learner is likely to improve their conceptual understanding.

As well as simulating real world systems, 3D environments can also represent abstract concepts. Hedberg and Alexander (1994) discuss the potential for such environments to represent real or metaphorical objects, attributes and conceptual relationships and suggest that the three-dimensionality of the virtual environment may allow the learner to incorporate these ideas into a three-dimensional cognitive model (p.216). Winn and Jackson (1999) concur, suggesting that virtual environments are “most useful when they embody concepts and principles that are not normally accessible to the senses” (p.7). They use the term ‘reification’ to describe the representation of phenomena that have no natural form. For example, they describe an environment that allows learners to control greenhouse gas emissions and to view models that metaphorically represent the effects of global climate change.

Ruzic (1999) also notes the potential for the use of metaphorical entities within virtual environments, suggesting that such environments incorporate two types of objects, “tangible (sensory) objects called sensory transducors, and the intangible, cognitive objects called cognitive transducors” (p.189). Sanchez, Berreiro and Maojo (2000) describe a model for developing educational virtual environments, which has the use of metaphorical models as a central component. They use the example of a 3D hierarchical model representing zoological taxonomies. They state that their aim as “to design and develop virtual worlds that provide visualisation of cognition”, describing visualisation of cognition as “the externalisation of mental representations embodied in artificial environments” (p.359). Salzman, Dede, Loftin and Chen (1999) suggest that virtual environments designed in this way can help learners to comprehend abstract information because of their “biologically innate ability to make sense of physical space and perceptual phenomena” (p.4).

Table 2 summarises the eight contributions to learning of 3D environments identified above. The first five identify contributions to a broad range of learning outcomes from recall of simple facts to complex problem solving. The last three, however, relate specifically to conceptual understanding, and it is argued here, are the most important in the context of this paper. The common thread in these three contributions is the implicit assumption that by exploring and manipulating a 3D virtual environment the learner will develop a spatial model of the concepts represented and that, for certain types of concepts, this spatial model is central to thorough conceptual understanding.

Contributions to Learning
Facilitate familiarisation of inaccessible environments
Facilitate task mastery through practice of dangerous or expensive tasks
Improve transfer by situating learning in a realistic context
Improve motivation through immersion
Reduce cognitive load through integration of multiple information representations
Facilitate exploration of complex knowledge bases
Facilitate understanding of complex environments and systems
Facilitate understanding of complex ideas through metaphorical representations

Table 2. Contributions of 3D Environments to Learning

The idea that actively exploring and manipulating a computer-based representation of ideas will lead to a stronger conceptual understanding is very consistent with constructivist theories of learning, especially those derived from Piaget’s theories (Jonassen, 1991). However, the assumption that a 3D environment explored on a desktop computer can lead to the development of a 3D spatial cognitive model needs further exploration. Specifically we need to look at studies into spatial cognitive models and spatial

perception and studies measuring the degree to which we develop such spatial models through 3D environment exploration. And if we can be confident that 3D environments can facilitate spatial knowledge development we need to investigate which of the learner-computer interactions unique to 3D environments are specifically important and what types of learning tasks are important in this process.

Spatial Perception

Many activities in our day-to-day life depend on our ability to recognise the three-dimensionality of the environment around us. The segments of information that we use to determine the three-dimensionality of objects within our environment are termed depth cues (Vince, 1995). Vince (1995) identifies four types of depth cues, visual cues, somatic cues (touch), aural cues, and vestibular cues (using our inner ear mechanism which senses the direction of gravity, rotation, and acceleration). Given that the particularly unique characteristics of desktop 3D environments are visual, only visual cues will be discussed here.

Cutting and Vishton (1995), in an attempt to isolate the most important cues involved in the visual perception of layout (depth perception), identify three groups of cues. The first group, primary cues, includes *accommodation*, *vergence* and *binocular disparity*. The second group, secondary cues, or *pictorial cues*, includes *occlusion*, *relative size and density*, *height in the visual field* and *aerial perspective*. The third group, *motion cues*, includes *motion parallax* and *motion perspective*. Ellis (1993) distinguishes between cues involved in the perception of a virtual image, including accommodative vergence and *stereoscopic cues*, and cues involved in the construction of a virtual space, including *perspective*, *shading*, *occlusion* and *texture gradients*. He also identifies cues involved in the virtualisation of the environment, which includes motion parallax. Combining those cues that are equivalent it can be seen that these authors identify a total of 13 cues. Table 3 lists and explains these cues as well as identifying which are available within desktop 3D environments.

The important thing to note in Table 3 is that of the thirteen visual depth cues identified, three are not available in desktop 3D environments. In order to judge how similar our depth perception in a desktop 3D environments is to real world depth perception it is important to determine the relative importance of the various depth cues. Cutting and Vishton (1995) compare the theoretical effectiveness of each of the visual depth cues for objects at various distances from the viewer. They find that accommodation and vergence are of negligible use for objects greater than one metre from the viewer and that binocular disparity becomes less useful for objects more than ten metres from the viewer. On the other hand occlusion, relative size, and relative density remain important regardless of the how far away the object is. Additionally they find that height in the visual field and motion perspective are more important than convergence, accommodation and binocular disparity for all objects more than a metre away. The most important result of this analysis for this study is that the depth cues not available in desktop 3D environments, namely accommodation, vergence and binocular disparity are very important only for objects very close to the viewer. Consequently, for objects more than a few metres away from the viewer within the virtual environment we should expect desktop 3D environments to provide a similar sense of three-dimensionality to viewing the same object in the real world, if other parameters such as field of view, texture resolution and the accuracy of the 3D model are comparable.

Cue	Explanation	Availability in desktop 3D
accommodation	The adjustment to the lens required to bring the object into focus	no
vergence	The convergence or divergence of the eyes required to produce an apparently single image	no
binocular disparity	The difference between the image as viewed by the two eyes	no
occlusion	The hiding of parts of an object by other objects	yes
relative size	The proportion of the view taken up by an object	yes
relative density	How close together objects appear	yes
height in the visual field	The up-down position within the visual field	yes
aerial perspective	The degree of atmospheric colour distortion (normally making objects appear more blue)	yes
perspective	The convergence of parallel lines going away from the viewer	yes
shading	The differences in apparent colour of surfaces depending on their angle from the light source	yes
texture gradients	The density of object textures (objects further away will have more dense textures)	yes
motion parallax	The change in occlusion of objects as the view position changes (especially moving left-right)	yes
motion perspective	Changes in object size and density as the view position changes (especially moving nearer-further)	yes

Table 3. Visual Depth Cues

Spatial Cognition

Spatial knowledge can be modelled as a set of entities with static and dynamic properties. Three distinct entities can be identified within our environment, each with properties to be understood. These are the space itself, containing immovable structures and landmarks, objects within the space, which move or change state under certain conditions, and actors whose actions cause changes within the environment. The space and the objects each have static properties that we need to encode, which essentially consist of their 3D structures. The dynamic properties encapsulate the way that the objects in the environment behave under certain conditions. They are characterised by relationships between the actors, the space and the objects. Figure 1 illustrates this model of our environment.

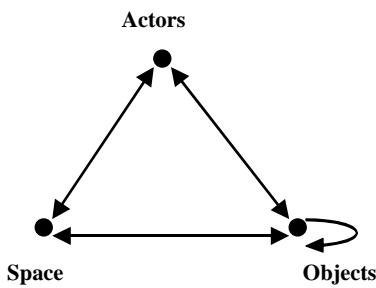


Figure 1. A Model of Spatial Knowledge

The way that we cognitively encode the static properties of objects is primarily addressed by the discipline of spatial cognition whereas the nature of the dynamic properties of our environment is informed by ecological psychology and environmental cognition (McLellan, 1996; Kitchin, 1994). According to Kitchin (1994), citing Hart and Moore (1973) spatial cognition includes a cognitive representation of the structure, entities and relations of the space, whereas, citing Moore and Golledge

(1973) Kitchin argues that environmental cognition refers to people's awareness, impressions, information, images and beliefs about an environment, which includes their knowledge of the functionality, dynamics and structural interrelatedness.

Studies of the way that we encode static properties of the environment are particularly important in the context of this paper because the learning potential of 3D virtual environments depends to a large degree on our ability to develop a related 3D spatial cognitive model. Such studies tend to focus either on our cognitive models of space, or of discrete objects. However, there are important similarities in the issues addressed and the conclusions reached. Specifically, the fundamental question of whether spatial knowledge is encoded in a view-dependent or view-independent way has been the focus of many studies of spatial cognition and object recognition.

Christou and Heinrich (1999) discuss the difference between a view-dependent and a view-independent model of the space around us. A view-independent representation (also termed an allocentric representation) is one where the space is encoded "according to view-independent features or components ... involving abstraction in order to reduce dependence on image-specific detail" (p.996). On the other hand a view-dependent representation (also termed an egocentric representation) uses "an image-based representation in which the spatial detail is represented only implicitly" (p.996) and space is encoded "with respect to the observer's body reference frame, as determined by experience." (p.996).

A number of studies have been undertaken to determine whether we use a view-dependent or view-independent representation, but the findings are inconclusive. For example, Christou and Heinrich (1999) note that studies showing that after viewing a scene from a number of directions people are able to recognise novel views, would tend to indicate a view-independent representation. However, they also note that "results from an increasing number of spatial layout studies suggest that although view generalization occurs to a limited extent around familiar directions, performance is reduced with increasing displacement of viewing perspective from the familiar directions" (p.997). This suggests a view-dependent representation. One of the reasons that studies addressing this issue have been inconclusive, is that, as pointed out by Hunt and Waller (1999), it is possible to exhibit view-independent behaviour even if we have a view-dependent representation, by computing new views from our remembered views.

Studies into the cognitive representation of objects by Bulthoff, Edelman and Tarr (1995) suggest that object representations are viewpoint dependent. Wallis and Bulthoff (1999), reviewing evidence from a large number of studies, suggest that objects are encoded using a linked combination of features. They propose that each feature is encoded as a series of two-dimensional views and is reused in the representation of multiple objects. Wallis (2002) suggests that our mechanism for collating the multiple images of each object (and possibly also the individual features of objects) that we store, is to use temporal information, on the assumption that images viewed very closely in time are likely to be views of the same object, either in different positions, if the object is moving, or from different angles, if it is rotating, or both.

Although the findings of both space and object studies are inconclusive, they present strong arguments that we encode the space around us and the objects within it using a complex network of two-dimensional views rather than a cohesive three-dimensional cognitive model, and that when we execute behaviours consistent with a three-dimensional representation, we are in fact relying on our ability to process recalled two-dimensional views in a complex way.

This is important because as well as being counter-intuitive, it contradicts the assumptions of a number of researchers into the learning benefits of 3D environments. For example, Hedberg and Alexander (1994) suggest that "as ideas are represented in a three-dimensional world, three-dimensional thinking can be enhanced, and the mental transformation of information from two to three-dimensions can be facilitated" (p.216). Similarly Moore (1995), in describing Osberg's (1994) Puzzle World, suggests that "the central hypothesis was that by teaching the students to think in 3D, using visualisation techniques their spatial cognition would be enhanced" (p.5).

This is not quite as discouraging as it first seems, however. Even if we don't actually form a three-dimensional cognitive model through exploration of a 3D environment, we may develop a larger database

of views and stronger mechanisms for retrieving and processing these views than through other means. Consequently, we may be better able to understand and negotiate the corresponding real world environment as a result. If the 3D environment is a metaphorical representation of abstract ideas, it may be that by developing an integrated database of two-dimensional views of a three-dimensional model of the concepts, we are better able to make sense of the concepts than through other instructional approaches.

Spatial Learning in Real and Virtual Environments

Having discussed the nature of spatial cognition we can now explore the effectiveness of 3D environments for developing spatial knowledge. A number of studies have compared spatial knowledge acquisition in virtual environments with spatial knowledge acquisition in similar real environments.

A study by Arthur, Hancock and Chrysler (1997) found that there was no significant difference between real world exploration and virtual environment exploration for drawing a map of objects and estimating inter-object distances within a single-room environment. A study by Richardson et al (1999) found that there was no significant difference between the performance of a real navigation group and a desktop virtual navigation group on a relative route estimation task or on a relative straight-line distance estimation task.

Ruddle, Payne and Jones (1997) note that studies comparing spatial knowledge developed in a virtual environment (VE) with spatial knowledge developed in the real world “suggest that either spatial knowledge is developed more quickly in the real world than in an equivalent VE or the ultimate accuracy of spatial knowledge developed in a VE is lower than that developed in the real world.” (p.144). In their own study they found that virtual environment navigation participants made less accurate direction estimates than real world navigation estimates but the differences were not large. They also found that virtual environment navigation participants had less accurate Euclidean and route distance correlations (relative distance estimates) than real world navigation participants, but the difference was not large. However, absolute distance estimates for virtual environment navigation participants varied widely and on average were nearly twice as bad as real world navigation participants.

A study by Christou and Heinrich (1999) found that navigation within a desktop virtual environment allowed participants to form cognitive models sufficient to allow them to identify novel views and topographical maps. In a study of the ability of participants to navigate through a maze blind-folded after learning the environment in the real maze, through an immersive virtual maze and through a desktop virtual maze, Waller, Hunt and Knapp (1998) found that real world participants performed significantly better than immersive and desktop VE participants in time taken to navigate through the maze. Witmer, Bailey and Knerr (1996) in a study comparing route-finding performance and configuration knowledge after rehearsal in a real building, a virtual building and using static images, found that a virtual environment “can be almost as effective as real world environments in training participants to follow a designated route”.

These studies provide strong support for the idea that people are able to develop spatial knowledge representations as a result of exploration of a virtual environment. They suggest that aside from the absolute dimensions of the environment, these spatial representations tend to be as accurate or nearly as accurate as representations formed as a result of exploring a real environment.

Towards a Research Agenda

From the above discussion, it is clear that perception of a 3D environment is comparable to real world perception. Although we might not necessarily form a 3D cognitive model, we are able to exhibit a degree of 3D understanding through complex processing of recalled 2D views and exploration of a 3D environment can lead to such a 3D understanding. Consequently we can be confident that 3D environments have potential in learning situations where a spatial cognitive representation is desirable. To proceed from here, however, there are a number of additional questions that need to be addressed. These questions relate to the specific aspects of 3D environments that are important in spatial knowledge development and the learning tasks that are appropriate in this process.

Drawing on the unique types of learner-computer interactions identified earlier and presented in Table 1, we can derive the following questions needing to be addressed by future research:

- How important is the perception of locomotion, dynamic changes in the orientation of objects and object animation in a 3D learning environment to the development of a spatial cognitive model?
- How important is user-controlled locomotion, object manipulation and user-control over object model parameters in a 3D learning environment to the development of a spatial cognitive model?

It is important to recognise, however, that merely providing an environment with a high degree of fidelity and user control, modelled on a real world system or a set of abstract concepts, will not necessarily facilitate the development of conceptual understanding. An appropriate set of learning tasks need to be designed, with appropriate task support, to ensure that the activities that the learners undertake as they explore the environment do in fact require them to develop such an understanding. This leads to the following additional questions to be addressed:

- What are the important characteristics of learning tasks within a 3D environment that will facilitate the development of a spatial cognitive model?
- What is the nature of the task support that is required for spatial knowledge development within a 3D environment, and how should this support be provided within the environment?

Once these questions are addressed developers of 3D learning environments will have a firm basis for their design decisions. Importantly, once more is known about the aspects of such environments that are important for learning, there will be a much greater likelihood that the resources developed will do more than simply impress the learner with technological ‘niftiness’ or visual realism, but will actually facilitate learning.

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