Perceiving Surfaces Oriented in Depth

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Environment Modelling and Depth estimation

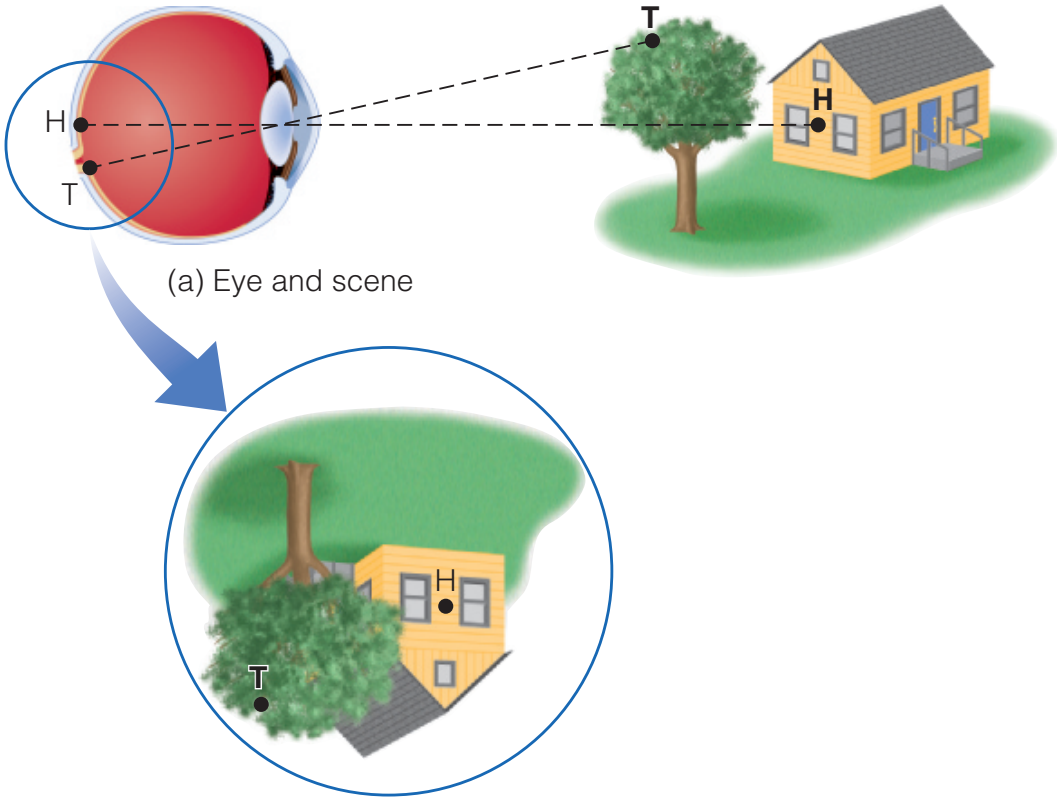
Indoor 3D modelling

Outdoor 3D modelling

Introduction

- Two of the three spatial dimensions of the environment are explicitly present in the 2-D images on the two retinae. (direction)
- The third dimension—the distance of the surface from the observer (depth) is lost in the process.
- The fact that people are very good at perceiving their 3-D environment demonstrates that surfaces in depth can indeed be accurately recovered from 2-D images.

How is this possible?



a) In the scene, the house is farther away than the tree, but images of points H on the house and T on the tree both fall on the two-dimensional surface of the retina on the back of the eye.

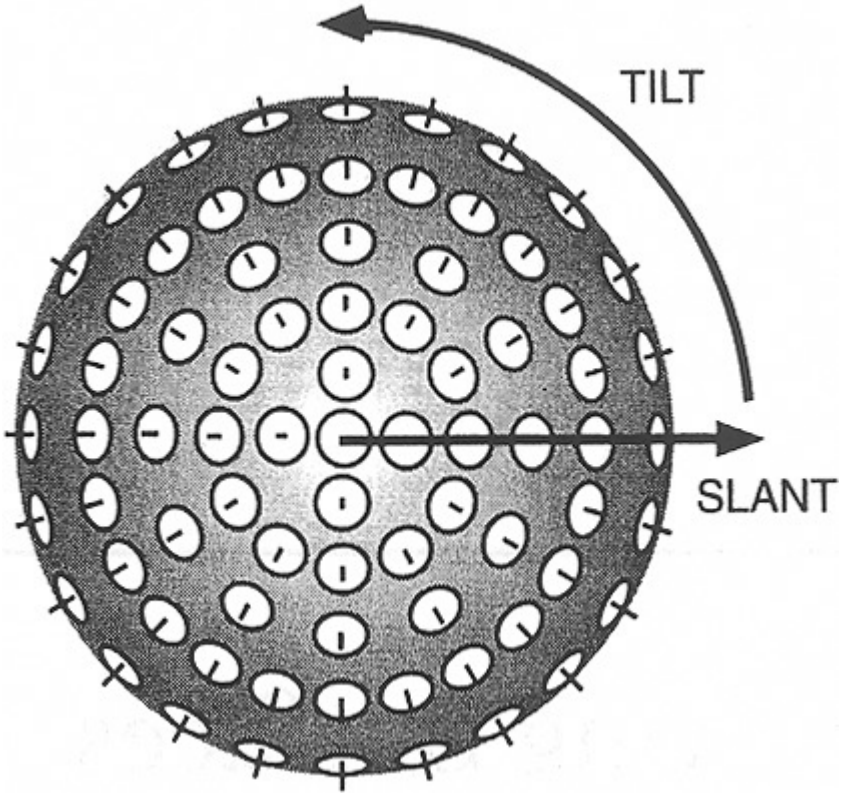
b) These two points on the retinal image, considered by themselves, do not tell us the distances of the house and the tree.

Introduction

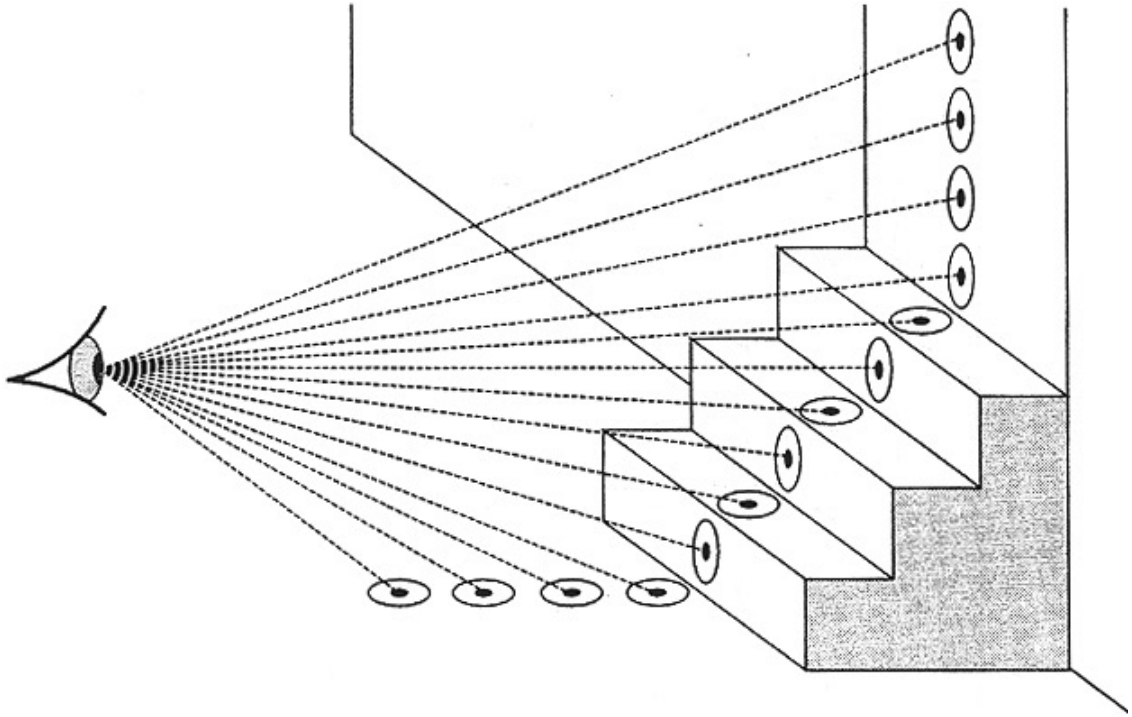
- The 2-D image features such as edges, lines, color, and texture elements, are important for vision.
- But they must be interpreted in terms of 3-D structure to make the inferential leap from image to environment.
  - The organisms aren't interested in edges between regions of different retinal luminance, color, or texture.
  - They are interested in edges between different environmental surfaces of objects.
- The interpretation of image structure in terms of visible surfaces in 3-D space is a crucial step in trying to solve the inverse problem.

Orientation: Slant and tilt

- **Slant**: the angle between the line of sight to the surface patch and its surface normal, as indicted by the degree of elongation of the ellipses and length of the line segments.
- **Tilt**: the direction of the surface's depth gradient, as indicated by the orientation of the ellipses and line segments.



Orientation at a distance



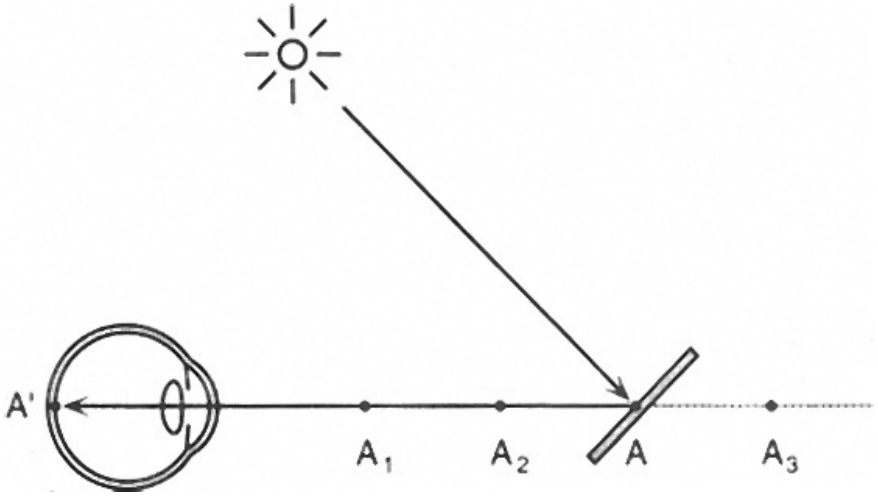
- Each patch can be characterized by its distance from the observer's eye and its orientation relative to the line of sight to it.

Depth and surface orientation

- They are two closely related problems that must be solved in perceiving the spatial arrangement of surfaces with respect to the observer.
- Depth and surface orientation are recovered together because they are intrinsically interdependent.
  - The 3-D orientation of a surface determines how far away its various parts are from the observer.
  - The distance of its various parts likewise determines its 3-D orientation.

1 The Problem of Depth Perception

- The depth perception from 2-D images is inherently ambiguous.
  - The reason: The optical processes project light from a 3-D world onto a 2-D surface at the back of eye.



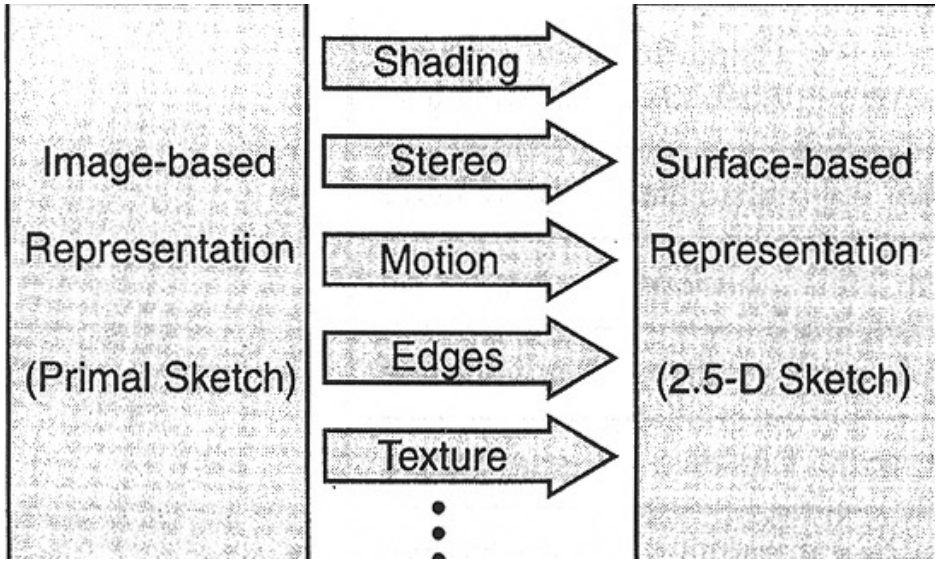
  - How does the observer know that the light didn't come from point A1, A2, or A3 instead of A?

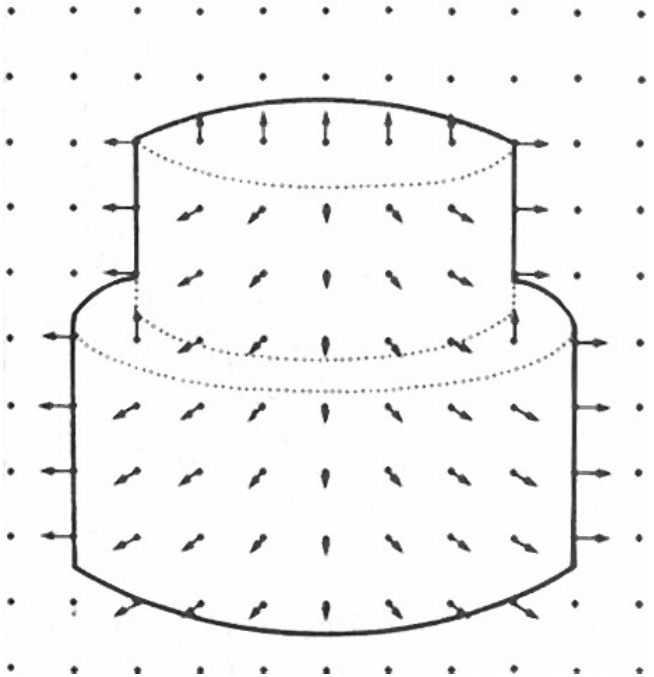
1.1 Heuristic Assumptions

- Depth illusory: flat photographs, motion pictures, 3-D movies, virtual reality displays
  - The depth that you perceive are completely flat.

- Normal everyday depth perception.
  - Together with the information available in the two retinal images, the heuristic assumptions are sufficient to recover depth information far more accurately than one would expect from the logical analysis given above.

1.2 Marr's 2.5-D Sketch





Sources of information about depth

- **Ocular** vs. **optical**: the state of the eyes, and the structure of the light entering the eyes
- **Binocular** vs. **monocular** information:
- **Static** vs. **dynamic**: motionless image, movement of the observer and/or the object
- **Absolute** vs. **relative**: actual distance to objects, how far objects are relative to each other.
- **Quantitative** vs. **qualitative**: numerical distance relations, ordinal relations of closer/farther.

Sources of information about depth

INFORMATION SOURCE	Ocular/ Optical	Binocular/ Monocular	Static/ Dynamic	Relative/ Absolute	Qualitative/ Quantitative
Accommodation	ocular	monocular	static	absolute	quantitative
Convergence	ocular	binocular	static	absolute	quantitative
Binocular Disparity	optical	binocular	static	relative	quantitative
Motion Parallax	optical	monocular	dynamic	relative	quantitative
Texture Accretion/Deletion	optical	monocular	dyanmic	relative	qualitative
Convergence of Parallels	optical	monocular	static	relative	quantitative
Position relative to Horizon	optical	monocular	static	relative	quantitative
Relative Size	optical	monocular	static	relative	quantitative
Familiar Size	optical	monocular	static	absolute	quantitative
Texture Gradients	optical	monocular	static	relative	quantitative
Edge Interpretation	optical	monocular	static	relative	qualitative
Shading and Shadows	optical	monocular	static	relative	qualitative
Aerial Perspective	optical	monocular	static	relative	qualitative

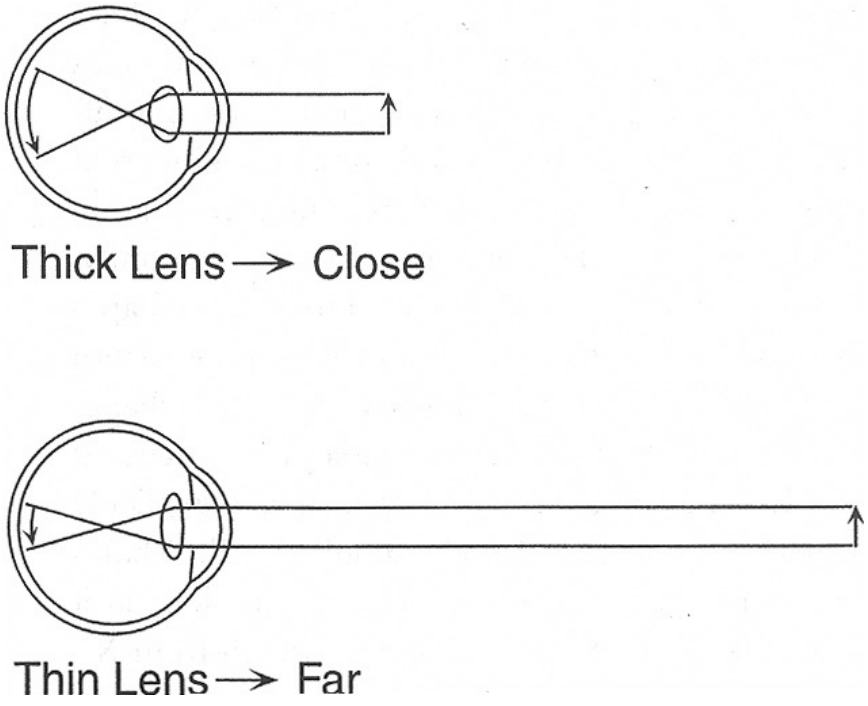
2 Oculomotor Information

- Oculomotor： Cues based on our ability to sense the position of our eyes and the tension in our eye muscles.

- Analogous information: mechanical and electronic apparatus controls for computer vision.

2.1 Accommodation

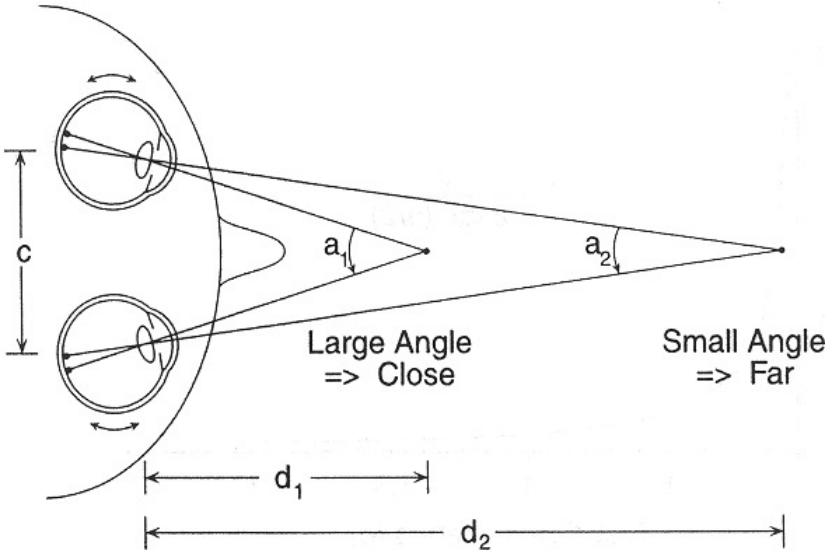
- Accommodation: the focus of the lens
- The process through which the ciliary muscles control the optical focus of the lens by temporarily changing its shape.
- If the visual system has information about the tension of the muscles that control the lens's shape, then it has information about the distance to the focused object.



- A weak source of depth information
- Absolute depth and monocular depth cue
- People use it at close distances, less that 1.8～2.4 meters.
- The object must be in proper focus on the retina: sharp edges vs. blurry ones
  - The visual system controls accommodation by adjusting the tension of the ciliary muscles so that the output of high spatial frequency channels is maximized.
- African chameleon, Near-sighted

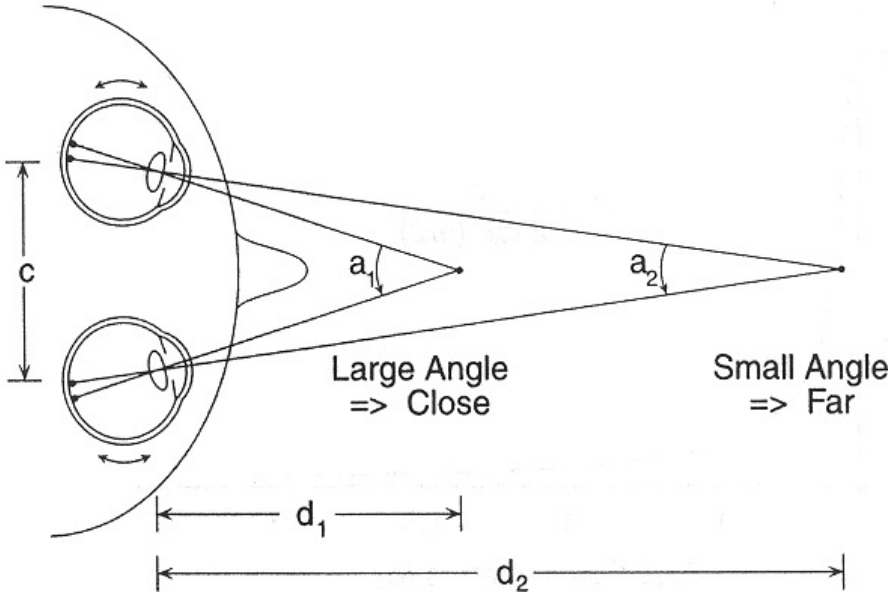
2.2 Convergence

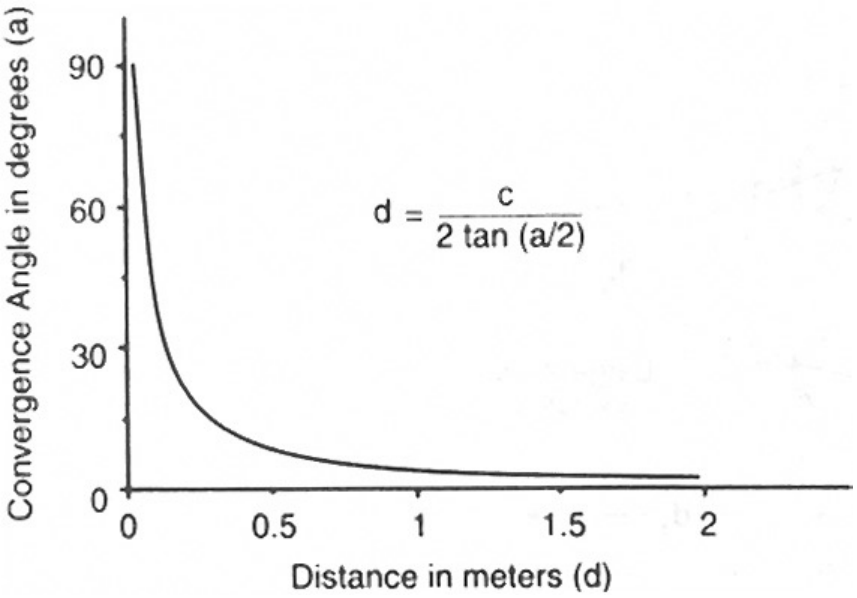
- The eyes fixate a given point in external space when both of them are aimed directly at the point so that light coming from it falls on the centers of both foveae simultaneously.



- The angle formed by the two lines of sight varies systematically with the distance between the observer and the fixated point.

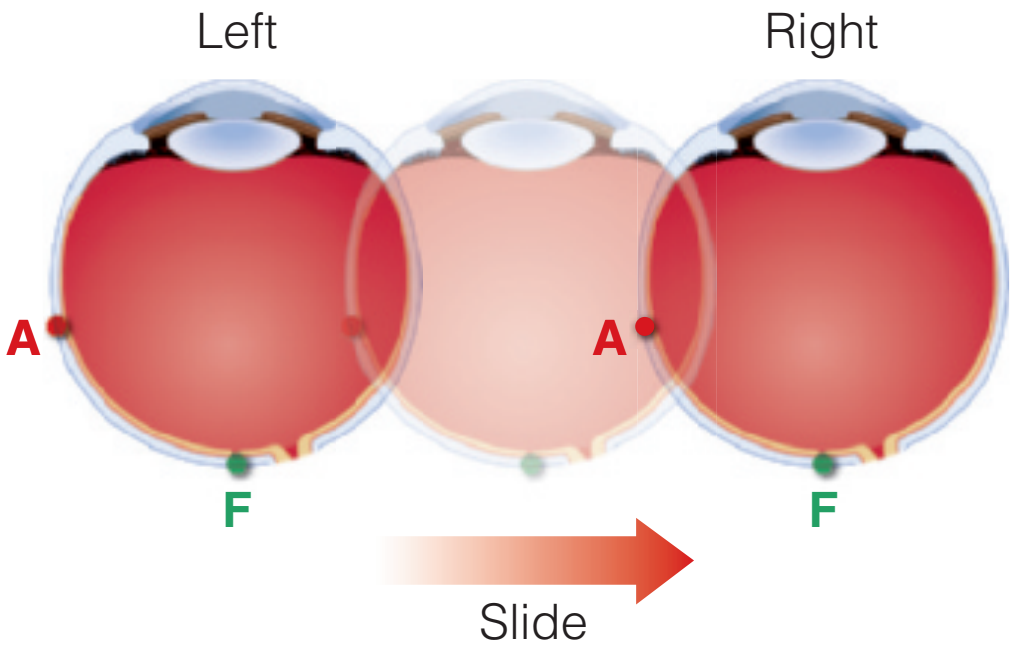
- Binocular depth cue
- The absolute depth
- Only up to a distance of a few meters.



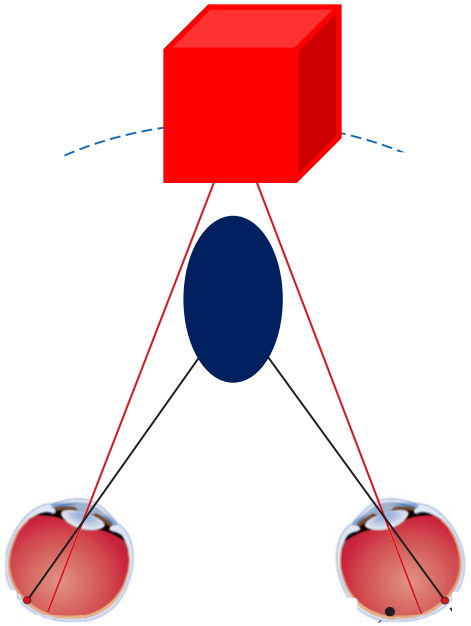


3 Stereoscopic Information

- Corresponding retinal positions
  - Positions on the two retinae that would coincide if the two foveae were superimposed by simple lateral displacement.



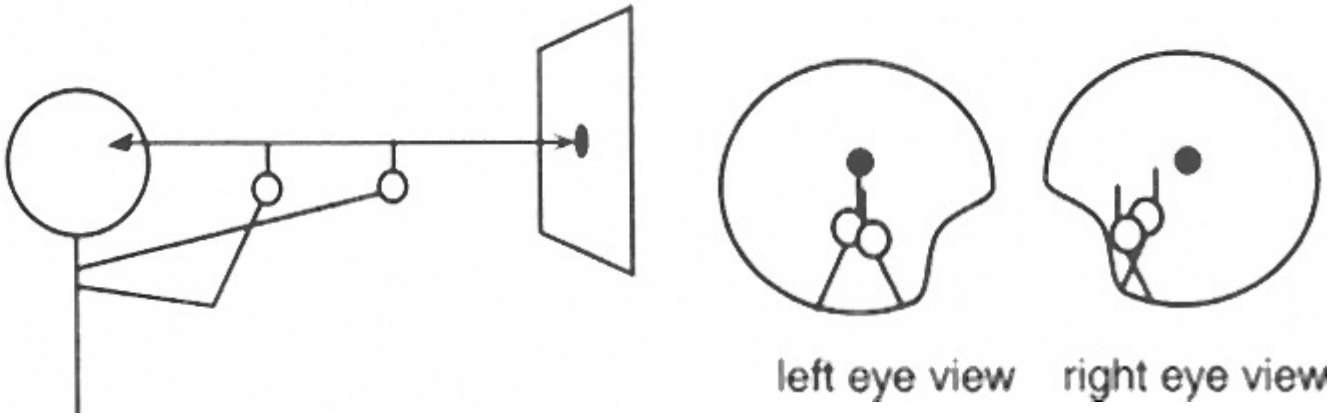
- Stereopsis: the process of perceiving the relative distance to objects based on their lateral displacement in the two retinal images.
  - The positions of the eyes differ by a few inches.
  - The two retinal images in the overlapping portion are slightly different.



- Binocular disparity: the same point in the environment projects to locations on the left and right retinae that are displaced in a way that depends on how much closer or farther the point is from the fixation point.

3.1 Binocular Disparity

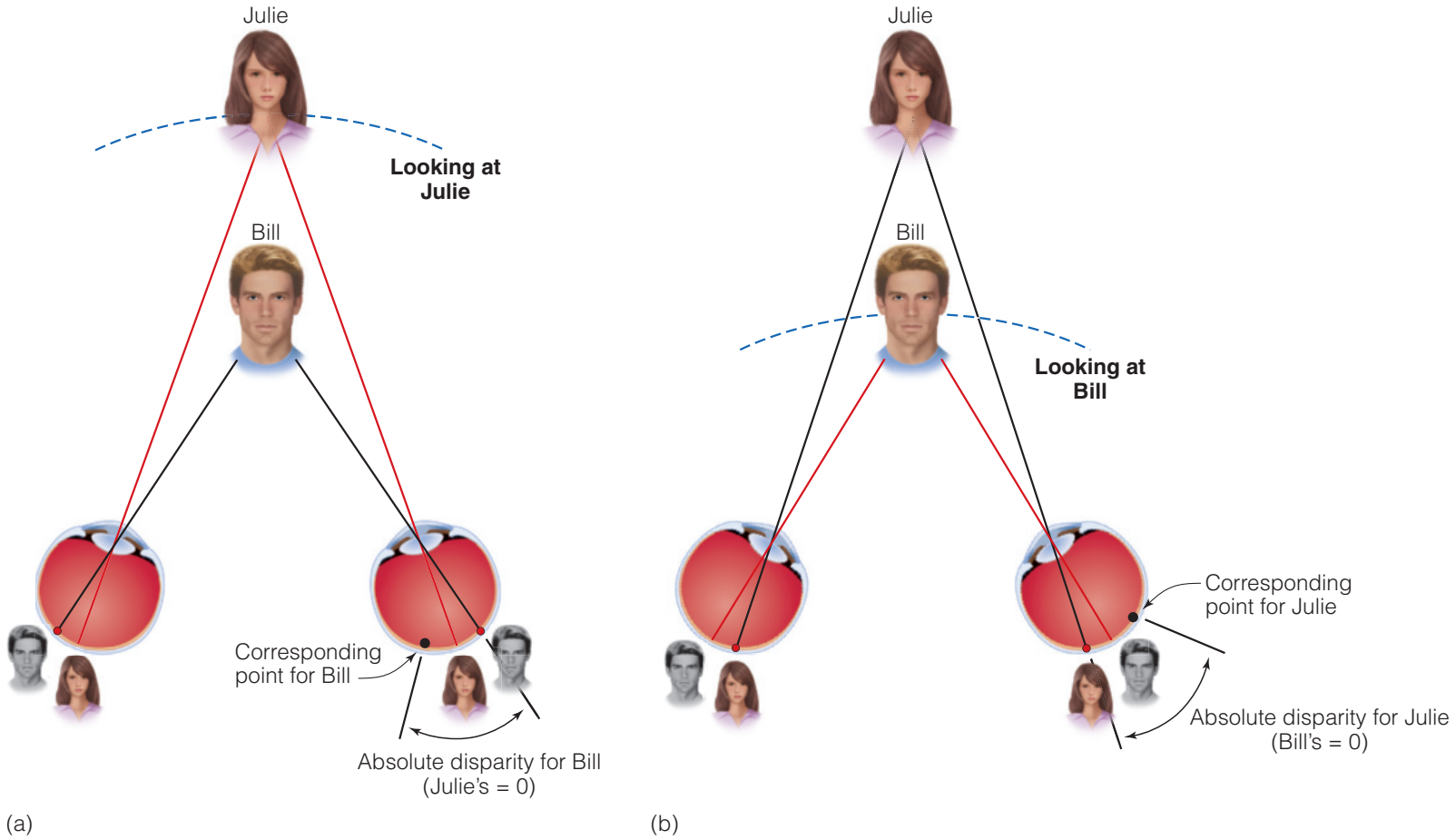
- You can experience the lateral disparity of corresponding points rather dramatically.
- Demonstration:



  - Close your right eye, focus on the distant object and align the fingers
  - Then close your left eye and open your right.
  - The few inches of separation between your eyes provide two slightly different views of the world.

Magnitude and direction of disparity

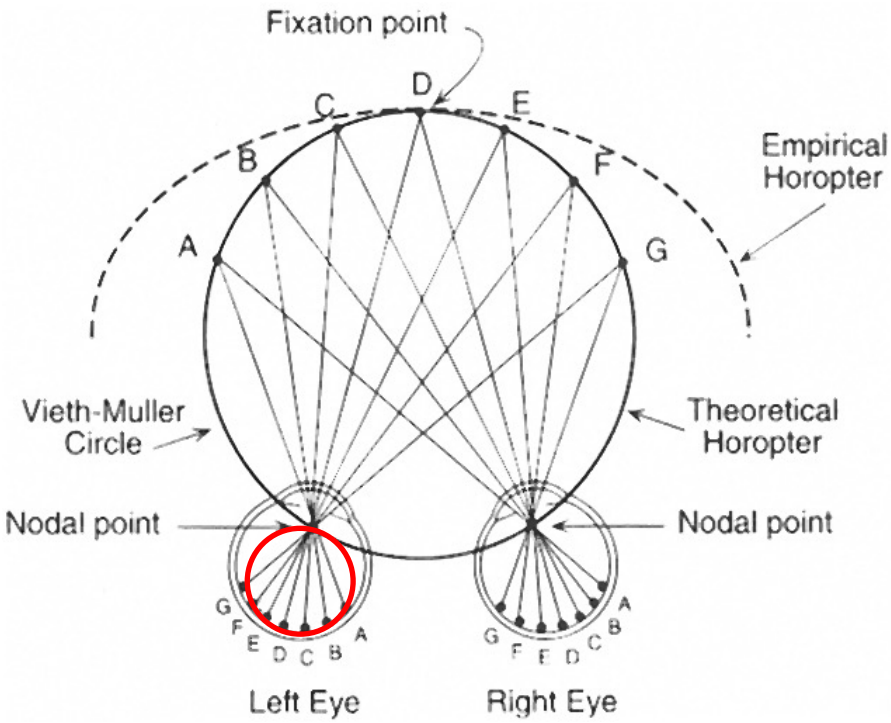
- When such disparity is registered by your visual system in two simultaneously present retinal images, it is interpreted as your two fingers and the distant object being at different depths.
- The ***magnitude*** of this disparity provides information about how much closer or farther they are, and specifies ratios of distances to objects. (making the close finger even closer.)
- The ***direction*** of disparity provides information about which points are closer and which are farther than the fixated point. (fixate the close finger)



- Binocular disparity arises when a given point in the external world does not project to corresponding positions on the left and right retinae.
- ***Crossed disparity VS. Uncrossed disparity***

The Horopter

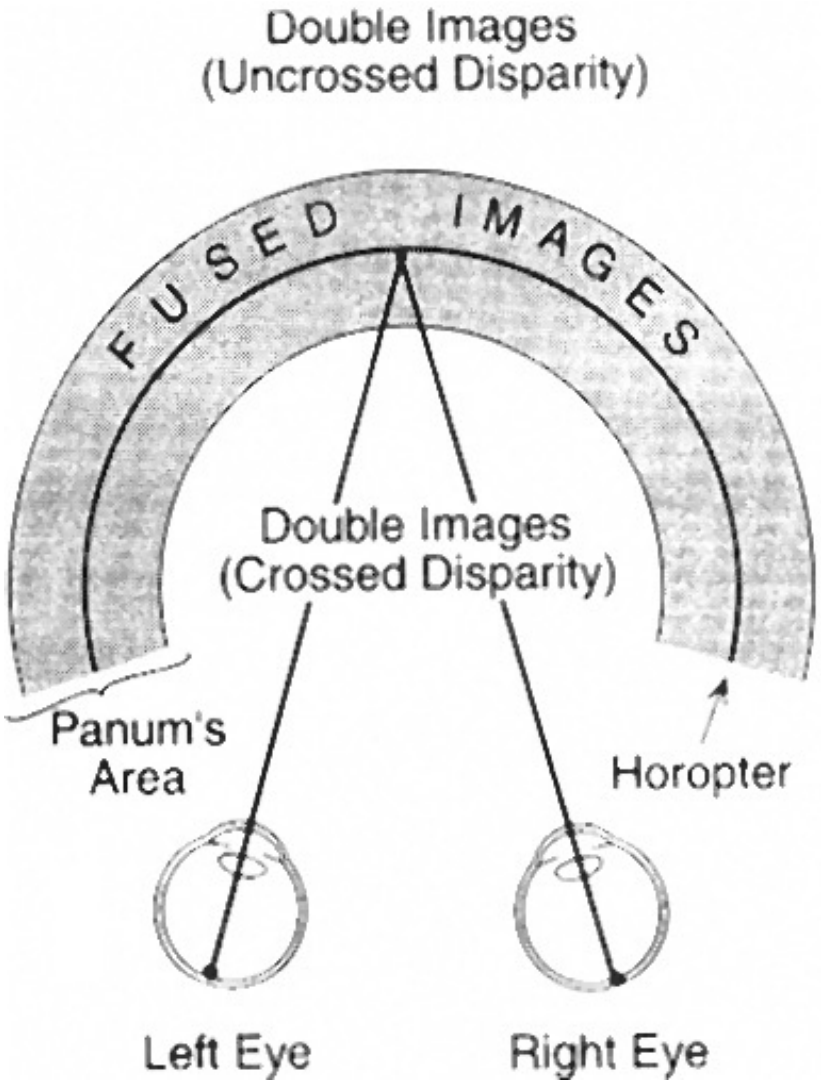
- Not all points in the environment produce disparate images on the left and right retinae, such as the fixation point, which falls on the center of both foveae.
- ***Horopter***: the set of environmental points that stimulate corresponding points on the two retinae.
  - The theoretical horopter: passes through the fixation point and the nodal points of both eyes.
  - The empirical horopter: the results of psychophysical experiments.



The horopter in the horizontal plane

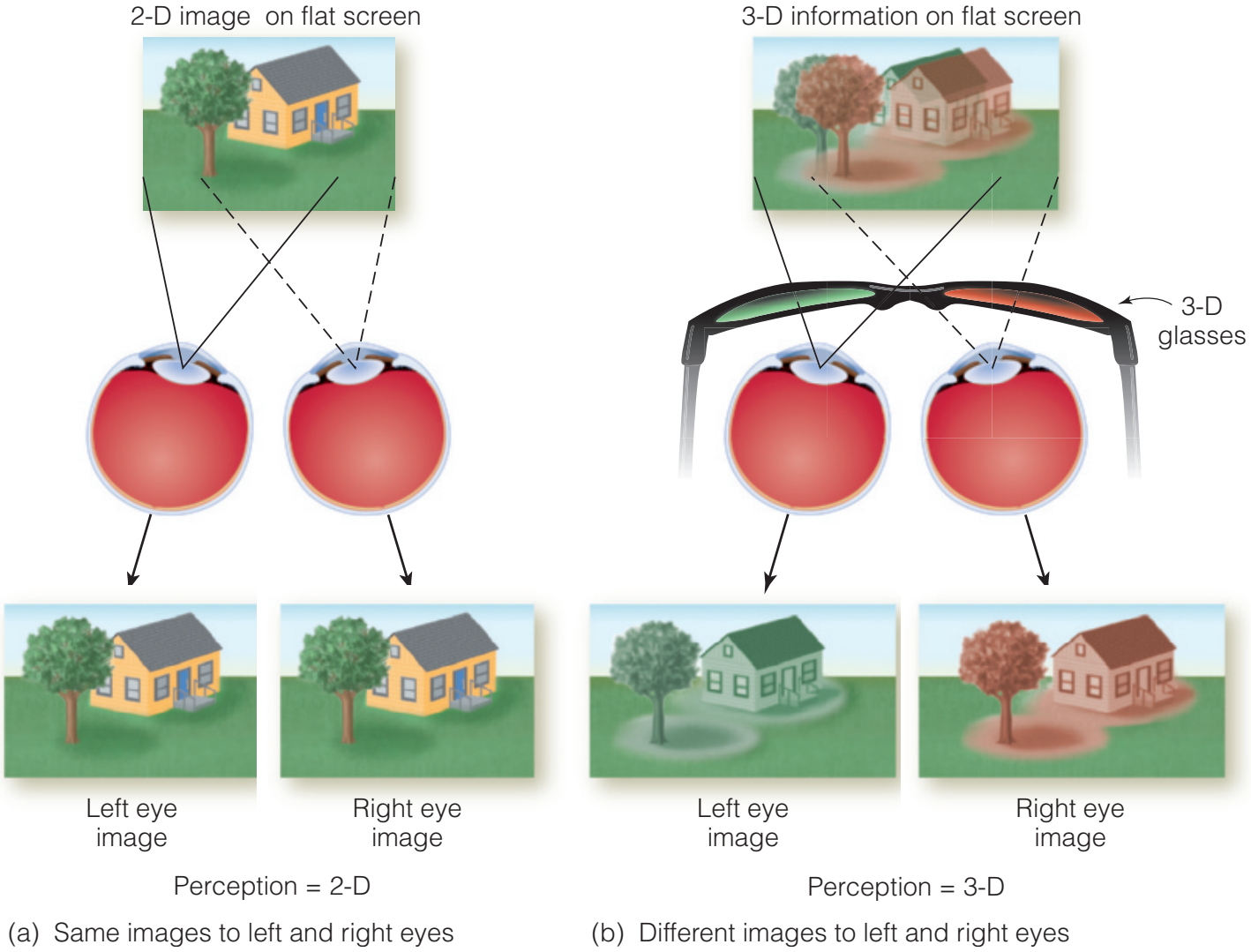
- Stereoscopic depth perception thus arises from different directions and degrees of retinal disparity for environmental points that lie in front of and behind the horopter.

- Double images demonstration: finger experiments
  - Fixate on the distant object with both eyes open
  - Fixate on your farther finger with both eyes open



Disparity (Geometrical) Creates Stereopsis (Perceptual)

- The **question**: why we don't normally experience double images?
  - The points on or near the horopter are fused perceptually into a single experienced image.
  - For points that lie outside Panum's area, the disparity is normally experienced as depth.
- Stereoscopic vision is exquisitely sensitive to binocular disparity.
  - Just a few second of angle (1/3600 of a degree)
  - The effectiveness is limited to a range of less than 30 meters.
  - Also limited to the central region of the visual field where the two retinal images overlap.
- Stereoblindness: 5%-10%, strabismus

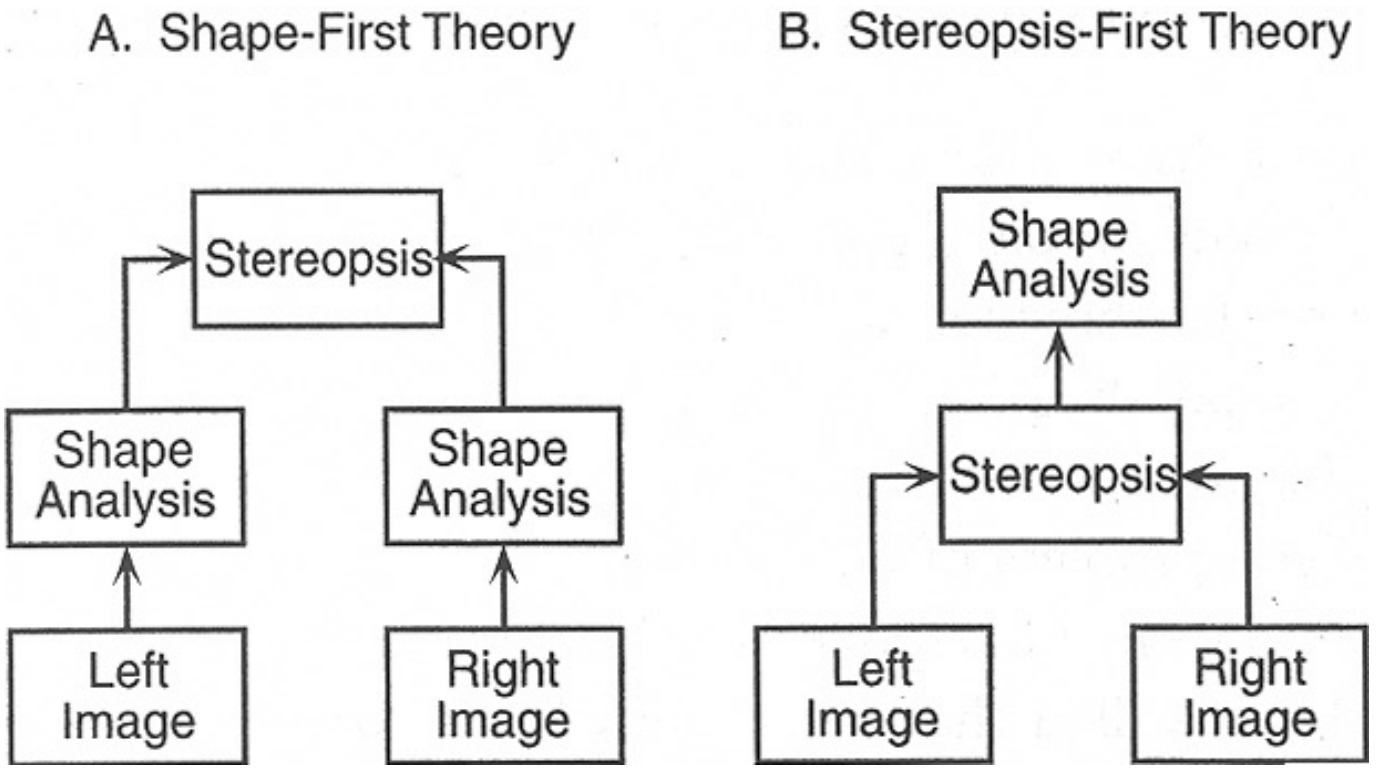


(a) When we view a two-dimensional movie, the left and right eyes receive essentially the same images, so depth is indicated only by monocular pictorial depth cues.
(b) When viewing a 3-D movie, the left and right eyes receive different images, so stereoscopic depth perception occurs.

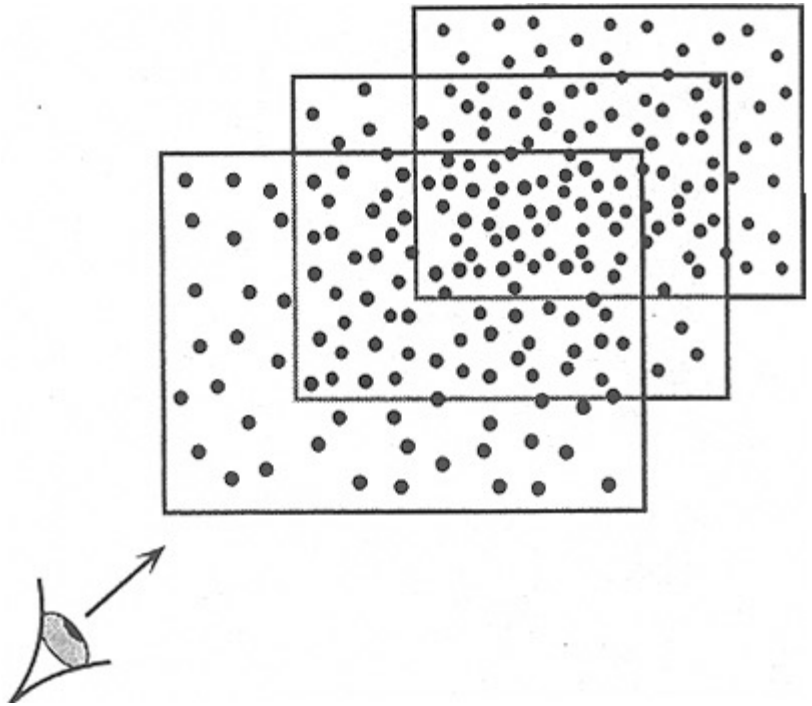
3.2 The Correspondence Problem

- The problems:
  - To measure the direction and amount of disparity between corresponding image features in the two retinal images.
  - To determine which features in one retinal image correspond to which features in the other.

Which one?


A. Shape-First Theory
Stereopsis
Shape Analysis
Shape Analysis
Left Image
Right Image
B. Stereopsis-First Theory
Shape Analysis
Stereopsis
Left Image
Right Image

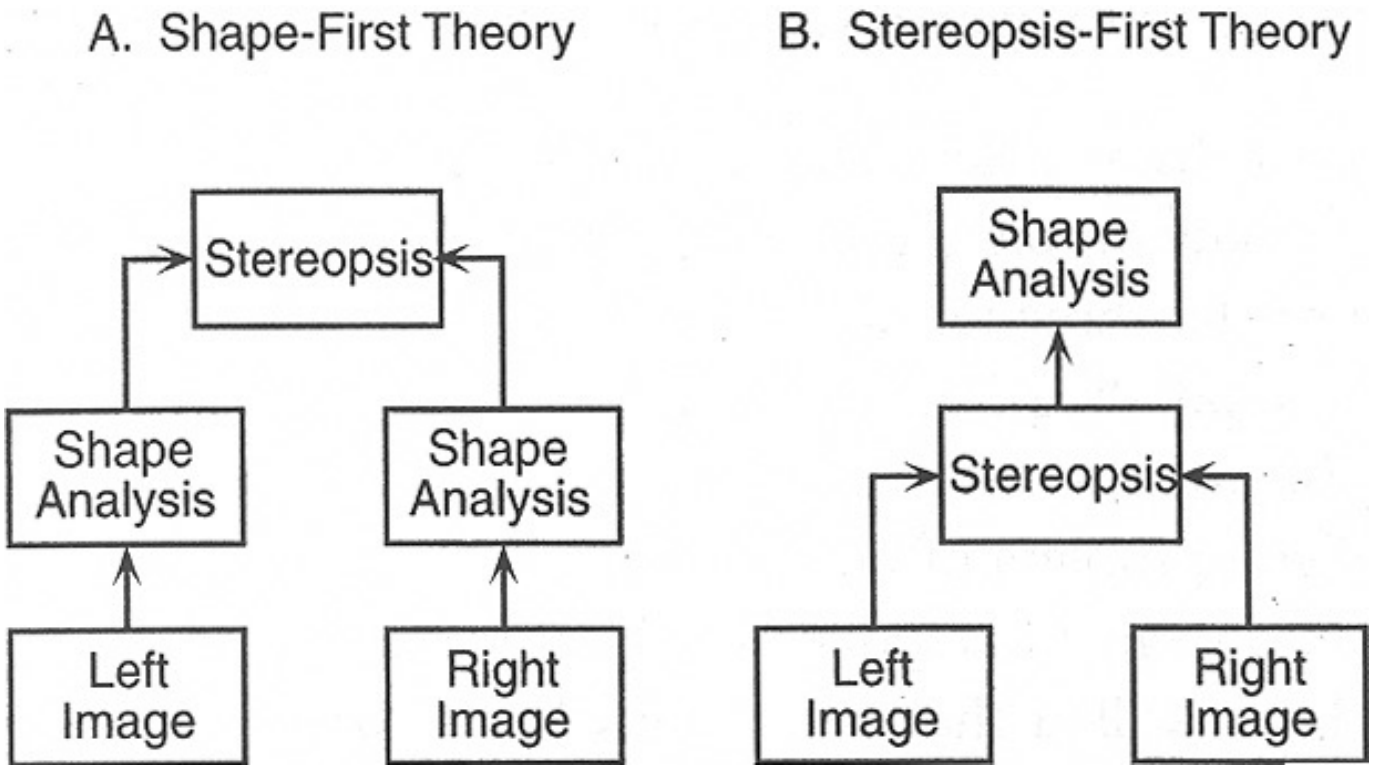
Random dot stereogram



Prazdny's stereo display:
1. Sparsely distributed dots
2. Transparent surfaces

This implies that mechanisms for solving the stereo correspondence problem exist at **a higher level** than has generally been supposed.

Which one?



OK

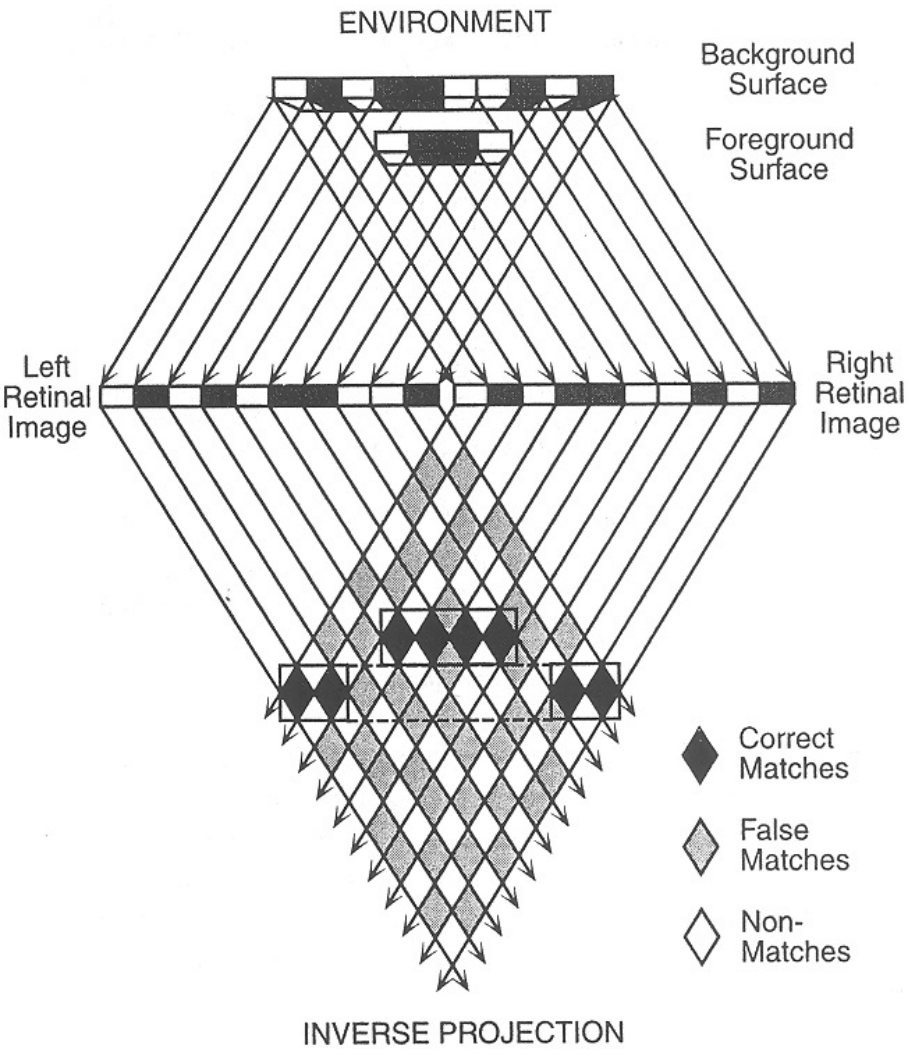
X

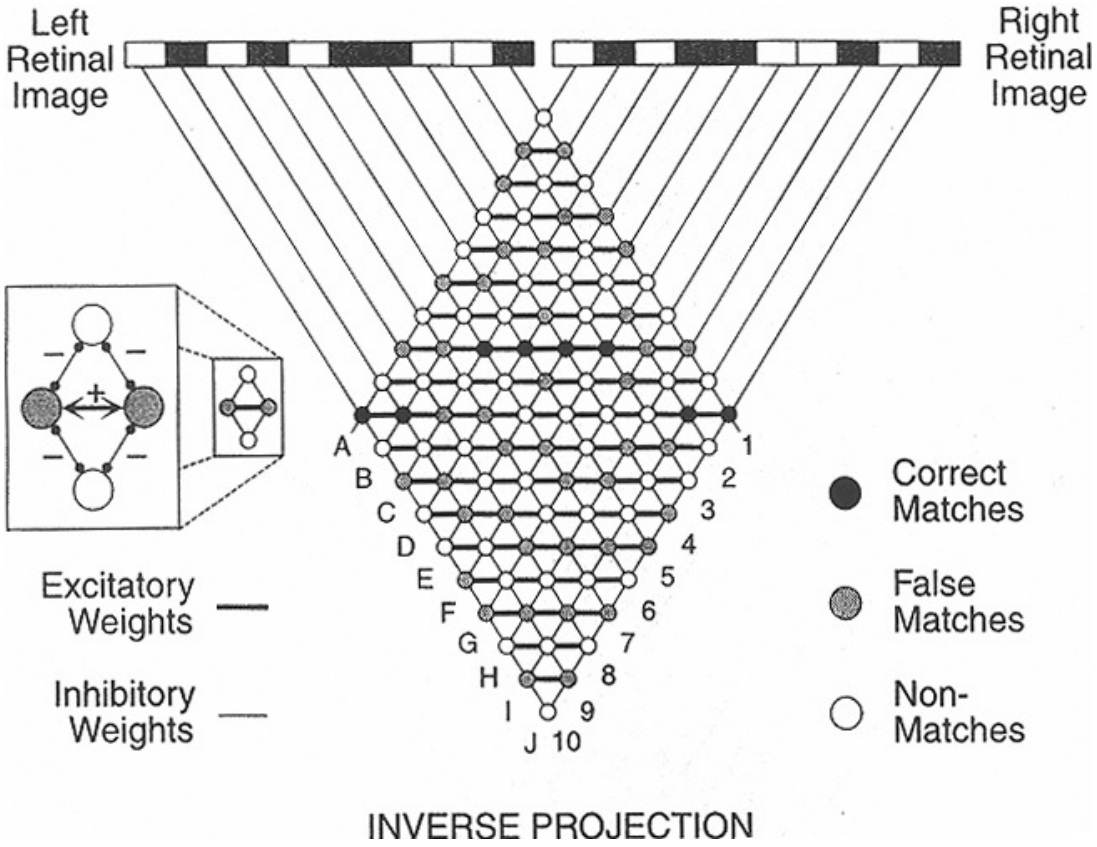
3.3 Computational Theories

- How does the visual system solve the correspondence problem in random dot stereograms when there is no global shape information?
- If there are 100 points along a given horizontal line in one image, then the number of logically possible pairings is 100!.

3.3.1 The first Marr-Poggio algorithm

- The problem for the visual system is how to determine which matches are correct and which are false?
- Two constrains:
  - Surface opacity:
  - Surface continuity:

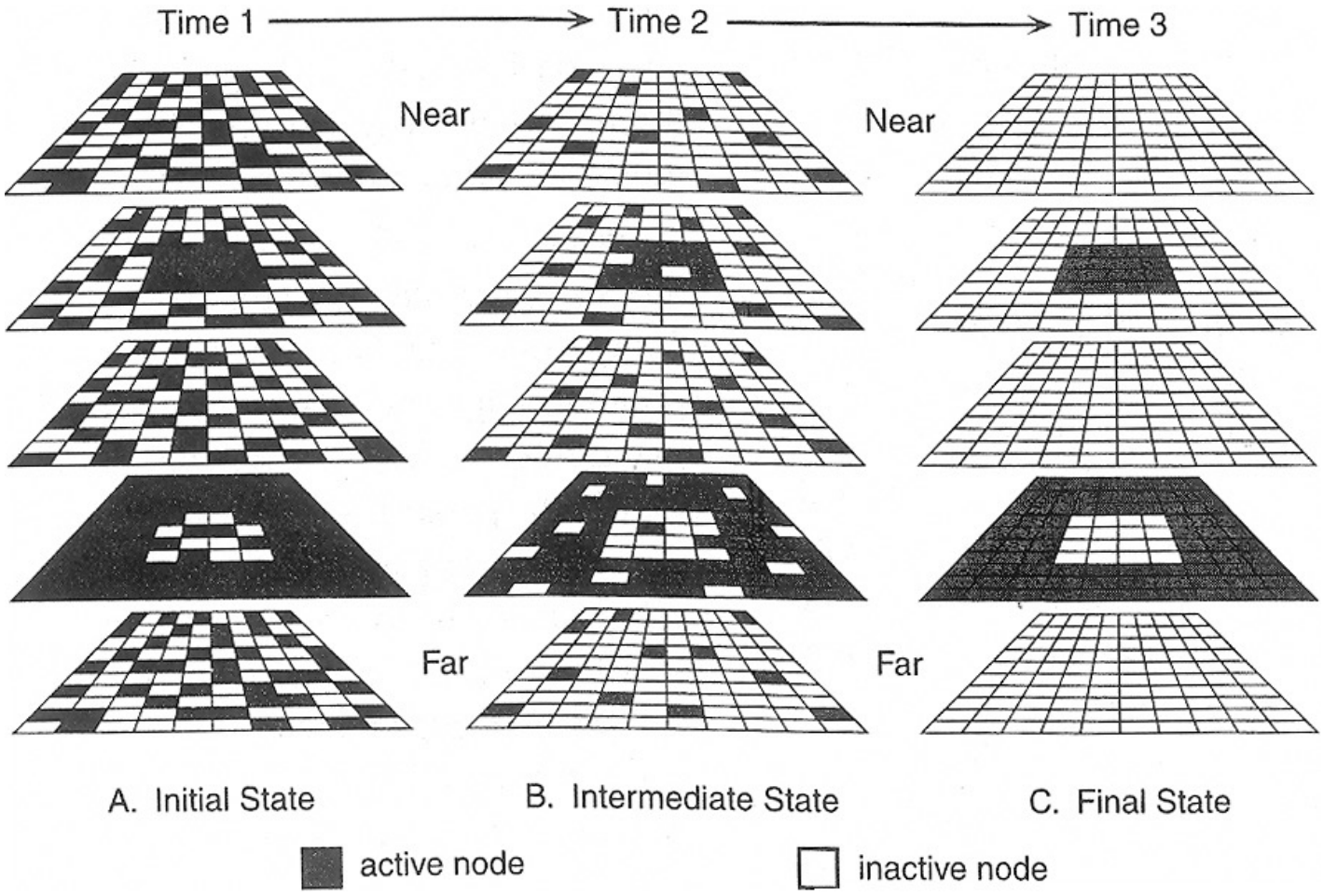




•Opacity is implemented by having mutual inhibition among all nodes along the same line of sight in the network.

Winner-take-all network: it allows only one node active

•Continuity is implemented in the network by having mutual excitation between pixels in the same or nearby depth planes.


Time 1
Time 2
Time 3
Near
Near
Far
Far
A. Initial State
B. Intermediate State
C. Final State
active node
inactive node

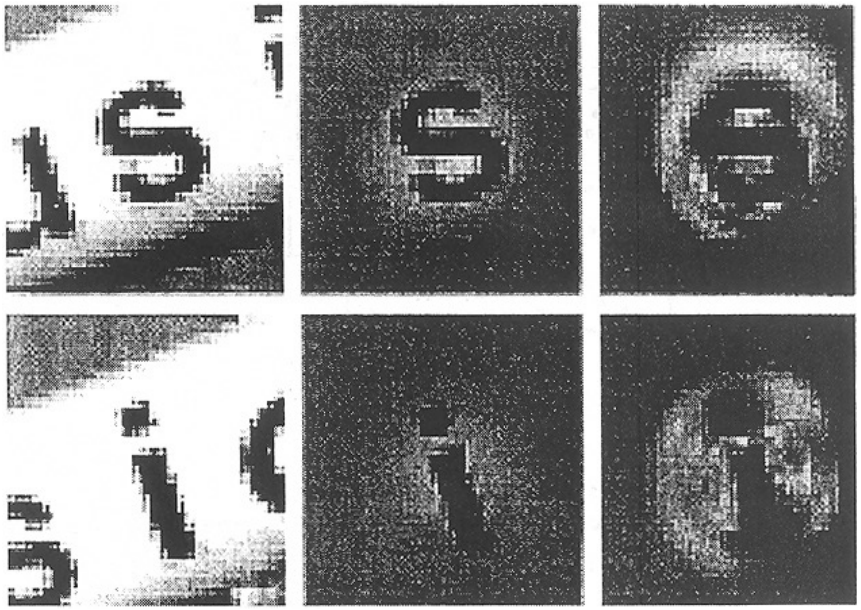
3.3.2 The second Marr-Poggio algorithm

Edge-based algorithms

- Edge-based matching: matching edges in the right and left images rather than individual pixels.
- Multiple scales: exploits the multiple size channels in the visual system by first looking for corresponding edges at a large spatial scale and only later at smaller scale.
- Single-pass operation: noniterative process

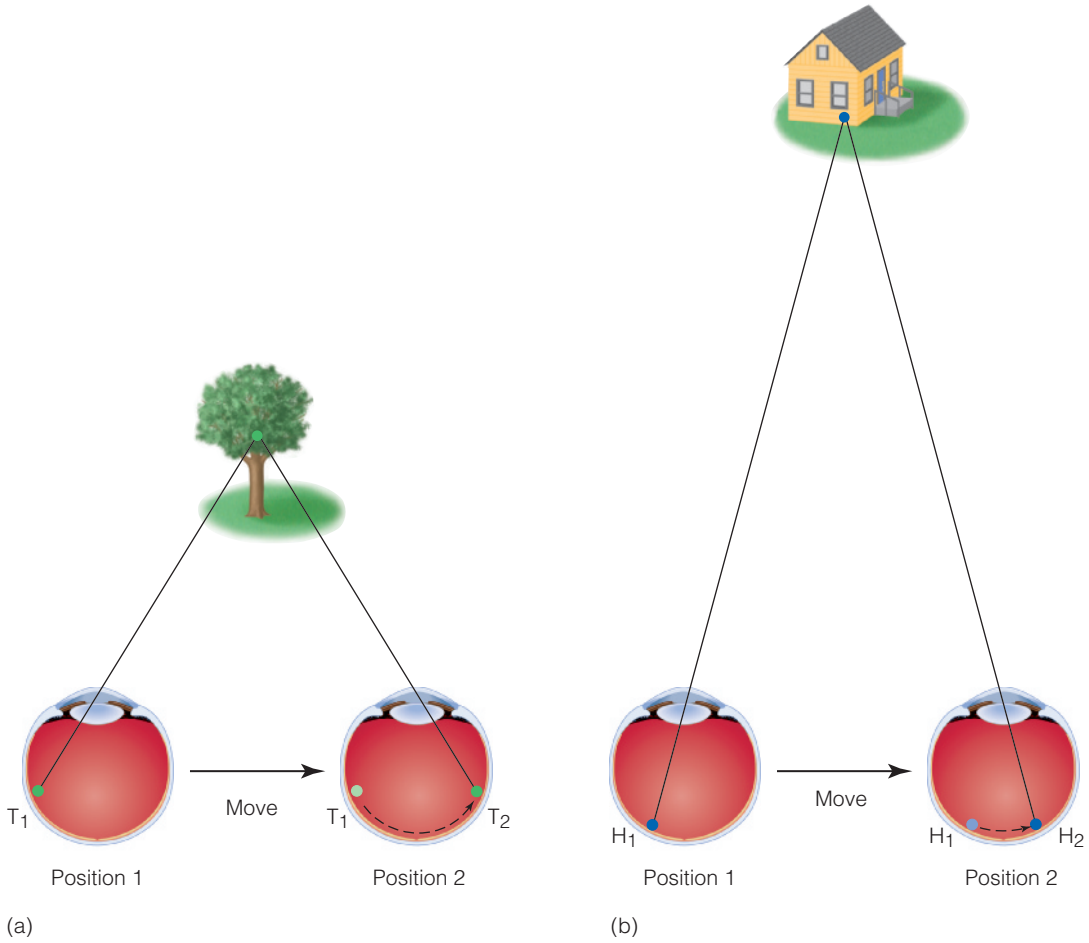
3.3.3 Filtering algorithm

- Local multi-orientation, multiscale (MOMS) filters:
  - Matches local regions around the point in question
  - Matching the output of a set of biologically inspired spatial filters that differ in their orientation and size tuning.



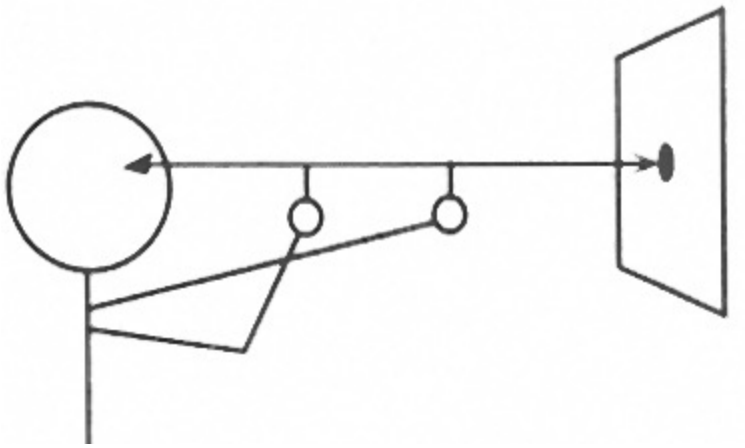
4 Dynamic Information

- When *an observer moves*, the direction and rate of the objects retinally depends *not only on the observer's motion*, but on ***how far the objects are*** and *on* ***where the observer is fixated***.



4.1 Motion Parallax

- **Motion parallax**: the differential motion of pairs of points due to their different depths relative to the fixation point.
- Demonstration:
  - Hold your finger. Close your right eye and align your two fingers with some distant object, focusing on it.
  - Keeping your fingers stilly, slowly move your head to the right. Notice that both of your fingers move leftward relative to the distant object, but the closer finger moves farther and faster.
  - And then move your head to the left.

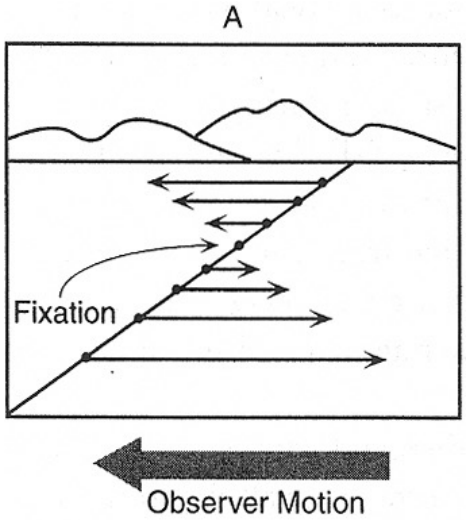


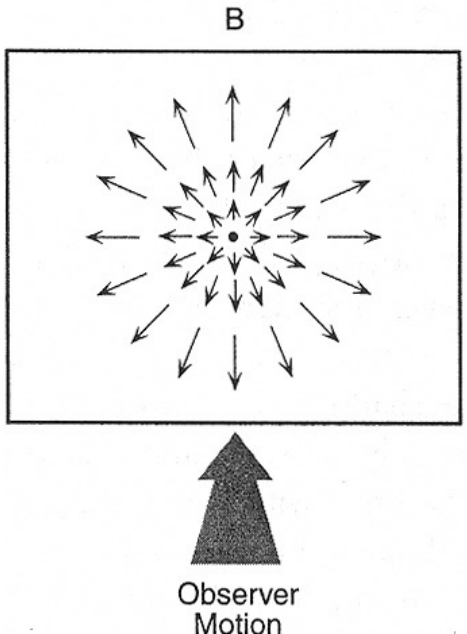
Binocular disparity vs. Motion parallax

- Binocular disparity involves the difference between a pair of displaced simultaneous retinal images.
- Motion parallax involves the difference between a pair of displaced sequential retinal images.
  - The pattern of retinal motion parallax actually reverses for different depths relative to fixation.
  - Motion parallax is also like binocular disparity in that it provides only relative information about depth.
  - Unlike binocular disparity, motion parallax can provide effective depth information at great distances.

Motion gradients

- The fixated point does not move on the retina, the rest moves at a speed and in a direction that depend on the depth relation between it and the fixated.
- ***Motion gradients***: the systematic changes in image motion, they were gradual changes in speed and direction.
- Optic expansion or looming:

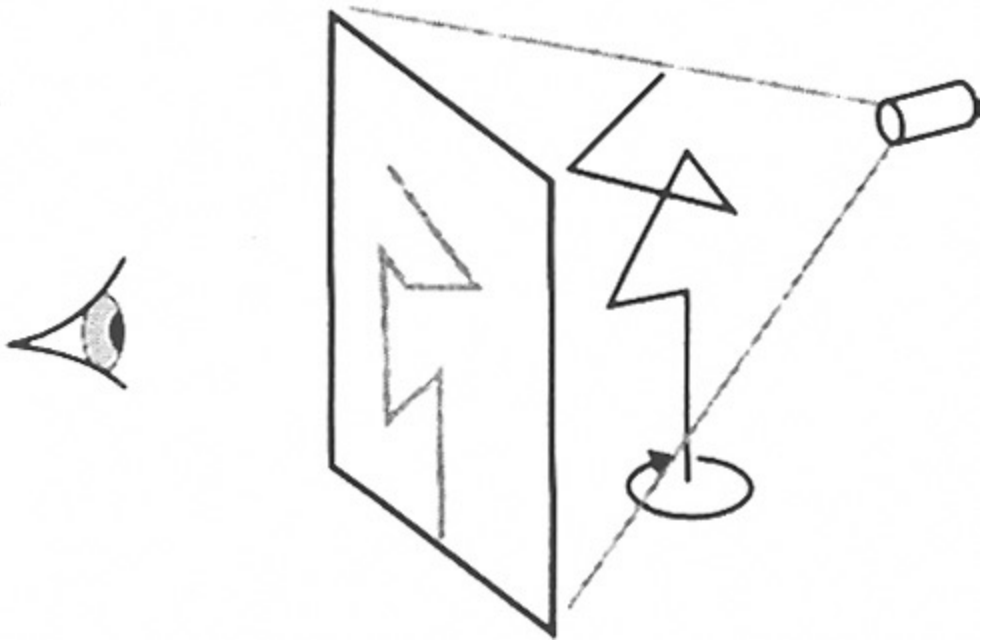




4.2 Optic flow caused by moving objects

- Depth information about a specific object becomes available when it moves with respect to the observer.
- The relative movement provides information about which points of the surface are closer and which are farther.
- The relative depth of the entire visible surface can be recovered from object motion so that its shape can be perceived.

Kinetic depth effect (KDE)



- It shows that depth information is clearly available from such dynamic displays.
- But ***where*** does it come from and ***how*** might the visual system make use of it?

Explanation

- Recovering depth from object rotation is geometrically underdetermined and therefore logically ambiguous.
- The 2-D retinal motion that arises from a 3-D object's rigid motion could be perceived as exactly what it is:
  - A 2-D figure that deforms nonrigidly over time.
  - There are many other deforming 3-D objects that would also project the same moving image on the shadow screen.
- **Rigidity heuristic assumption**: a bias toward perceiving *rigid motions* rather than *plastic deformations*, provided the sensory stimulation is consistent with such an interpretation. Because rigid motions are much more probable than corresponding plastic ones.

5 Pictorial Information

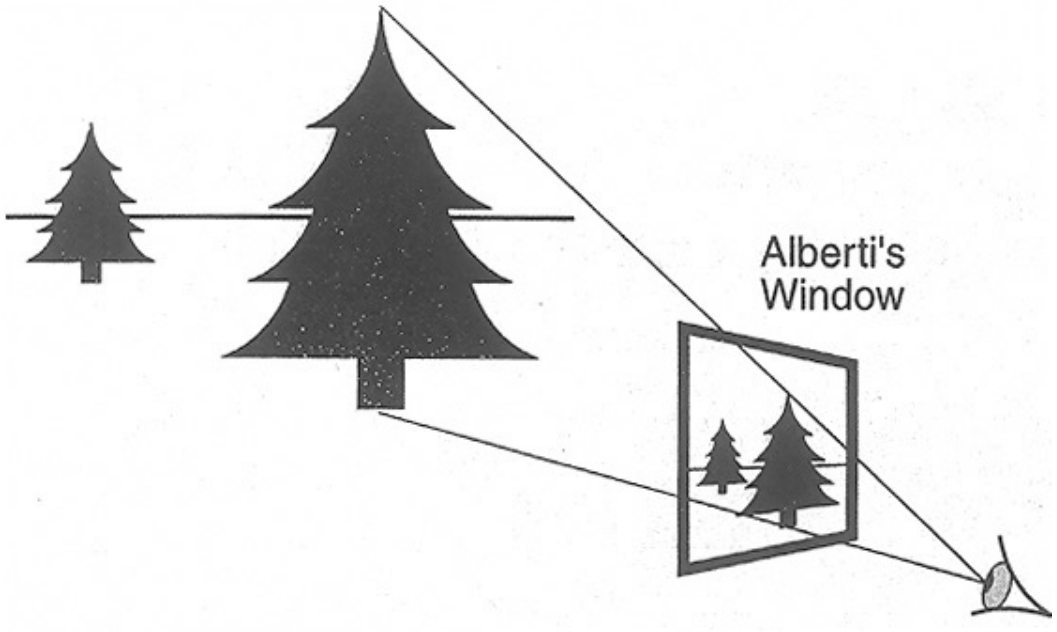
- **Pictorial information**: depth information available in static, monocularly viewed pictures.

5.1 Perspective Convergence

- **Perspective projection** produces differences between real-world objects and their optical images.
  - 3-D objects and scenes produce images that are only two-dimensional. The depth is lost.
  - 2-D images formed by perspective projection actually contain a great deal of information about this “lost” dimension that allows it to be recovered, even though imperfectly.

Alberti's Window

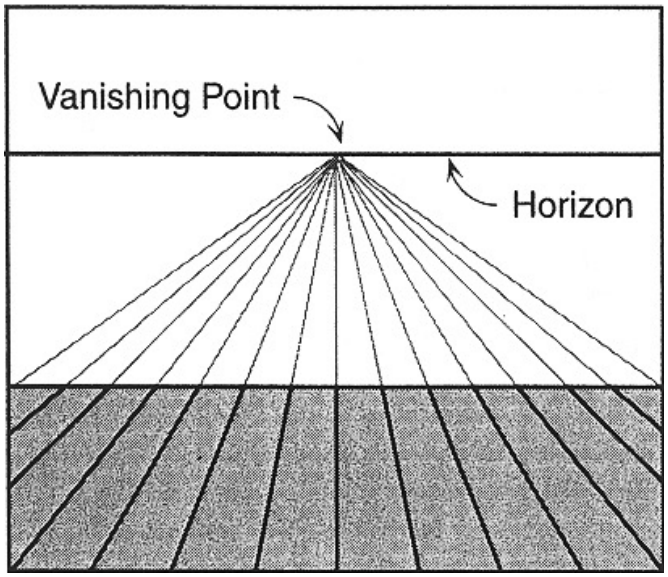
- In 1463, an artist named Alberti described a method for drawing pictures in proper perspective that revolutionized the artistic representation of depth.

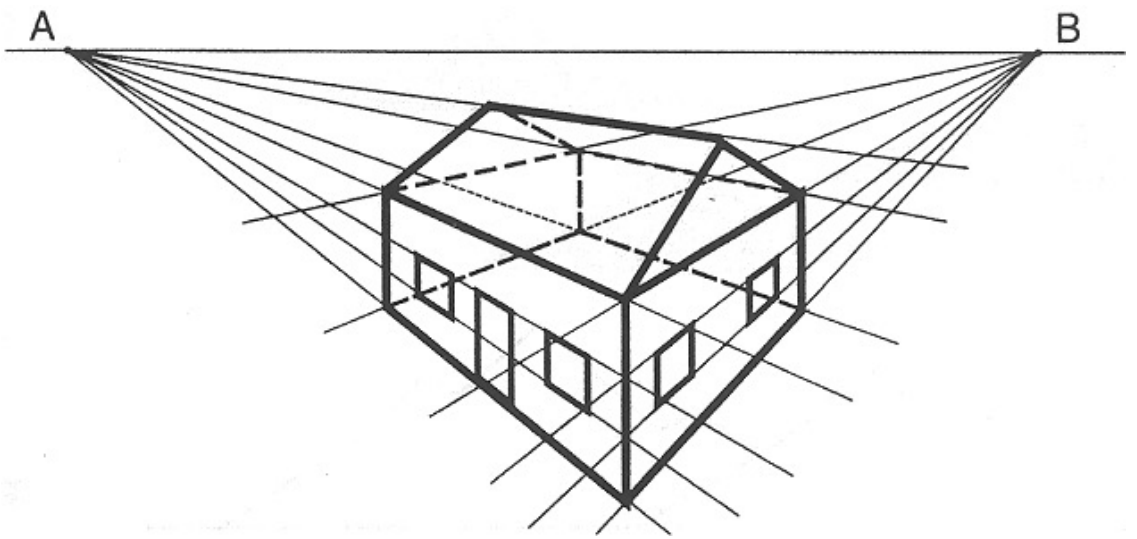


- Perceiving depth in pictures is a form of illusion because pictures are actually quite flat.

Convergence of parallel lines

- Parallel lines in the 3-D environment do not project as parallel lines in the 2-D image, but as lines converging toward a vanishing point on the horizon line.
- All parallel lines in any plane converge to the same vanishing point.



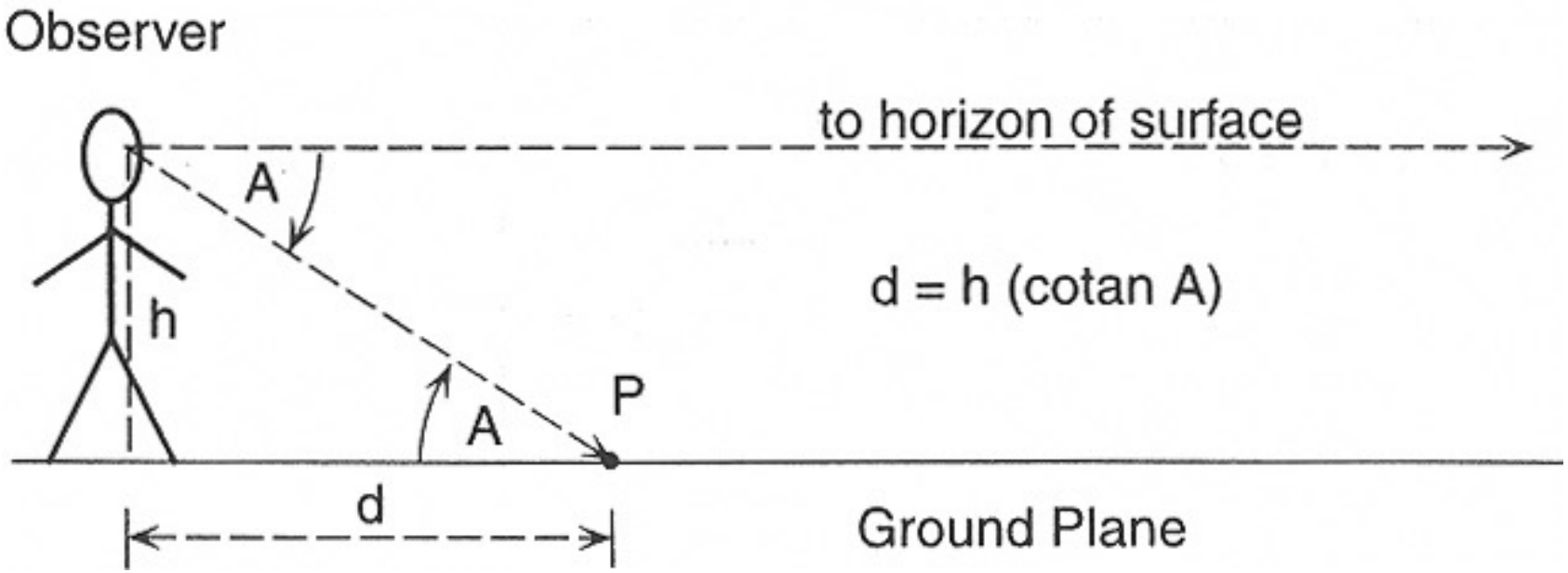


The convergence of lines on the plaza illustrates perspective convergence.

5.2 Position relative to the horizon of a surface

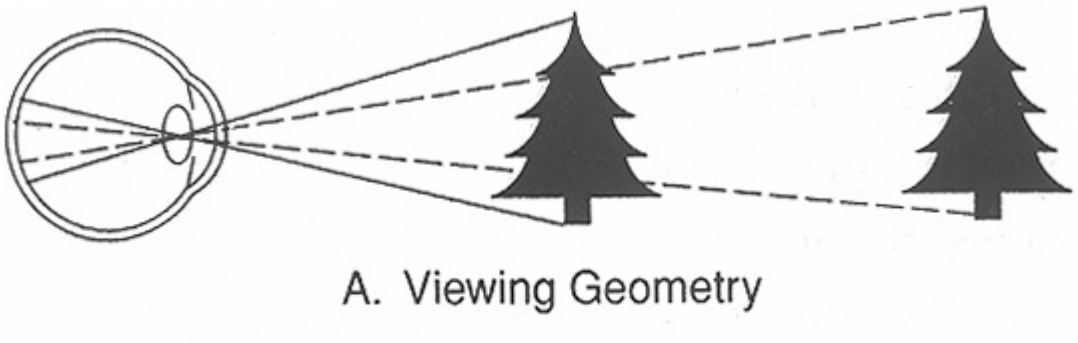
- The reason for these perceptions is the placement of objects on a plane relative to its horizon line.
- All objects on a level plane, the ones closer to the horizon in the picture plane are perceived as being farther away.

- Quantitative information is available if the horizon is visible or can be determined from visible information.

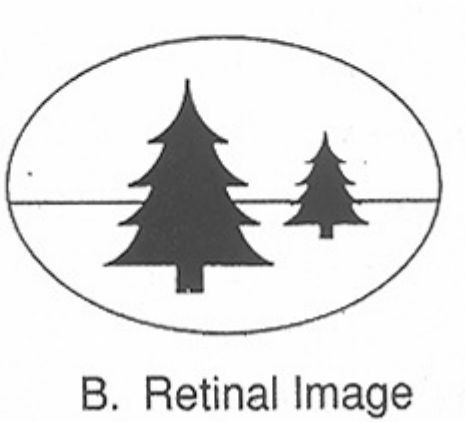


5.3 Relative size

- All else being equal, more distant objects project smaller images onto the retina.



A. Viewing Geometry



B. Retinal Image

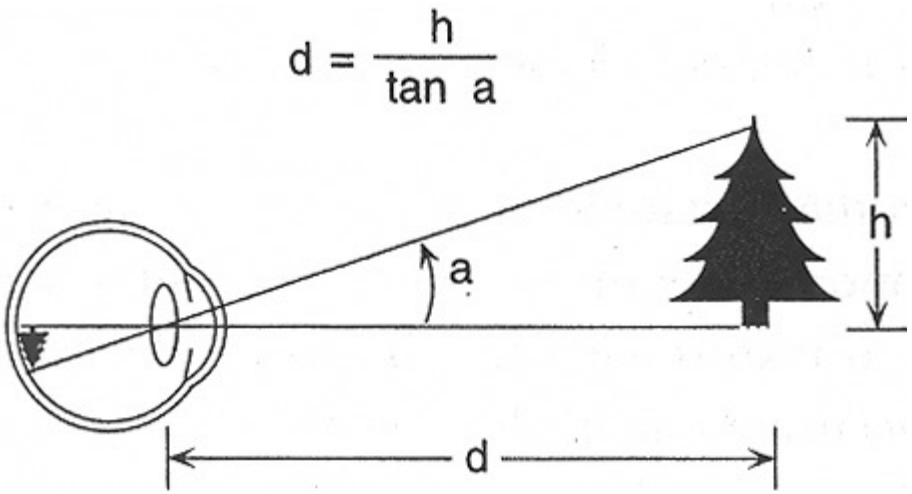
- Relative size as a cue to depth:
  - Two retinal images, similar except for retinal size, are actually the same size in the environment
  - The depth information can be computed.

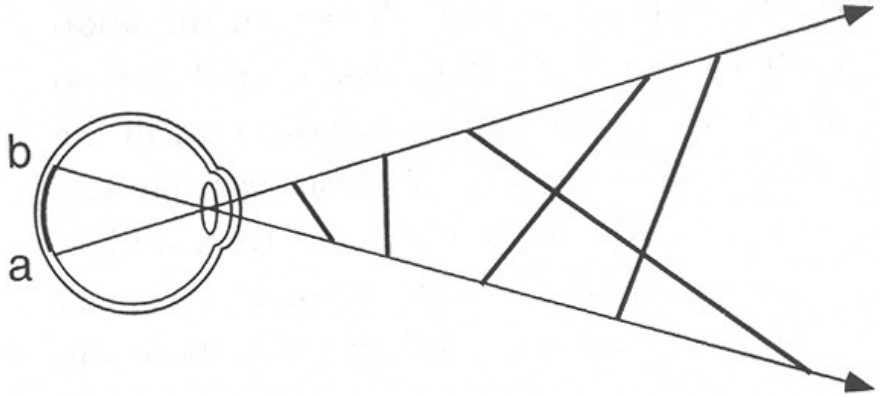
5.4 Familiar size

- If the size of an object is known to the perceiver, then the size-distance equation can be solved for its actual distance from the observer.
- It is rapid, unconscious process.
  - Examples: A dime, a quarter, and a half-dollar under monocular viewing conditions in a darkened room.

Dime Quarter Half-dollar

Size-distance relation





- Problem: the actual size of the object (h) must be known as well.

5.5 Atmospheric perspective

- **Atmospheric perspective**: refers to certain systematic differences in *the contrast and color of objects* that occur when they are viewed from great distances. Such as ***building*** far away
- The contrast is reduced by the additional atmosphere through which they are viewed, because it contains particles of either dust, water (fog, mist, humidity) or pollutants (smog) that ***scatter light***.
- Artists have long used atmospheric perspective in portraying distant landscapes in their work.

5.6 Texture gradients

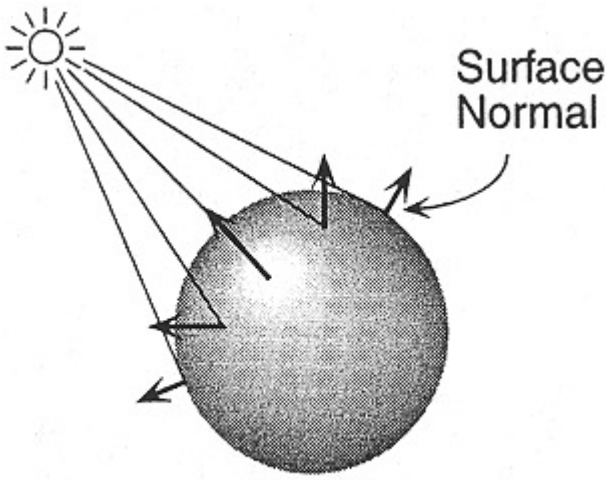
(a)

(b)

- Texture gradients: systematic changes in the size and shape of small texture elements that occur on many environmental surfaces.
- Texture gradients provide depth information and the orientation of a surface in depth.

5.7 Shading information

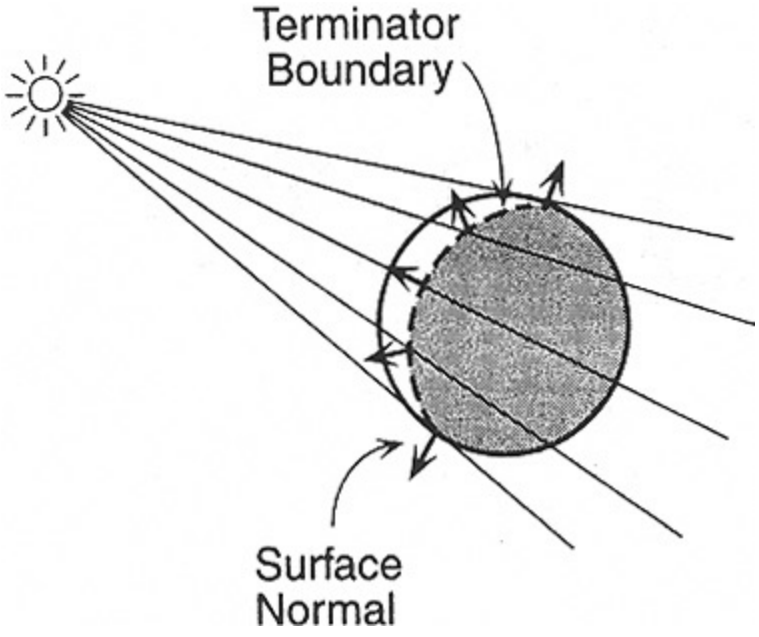
- **Lambertian surface**:
  - Homogeneous **matte** material that diffuses light uniformly in all directions. (A single distant point source)
  - ***The brightest part*** of its surface is where the surface normal points directly back to the light source.
  - As the angle between the surface normal and the incident light increases, the amount of light reflected into the eye decreases, producing a ***shading pattern***.



Lambertian Sphere

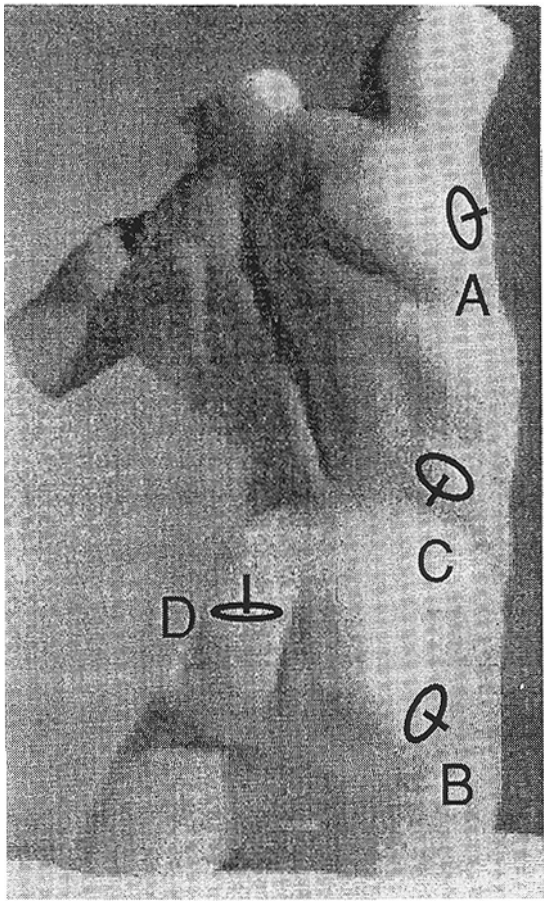
Horn's computational analysis

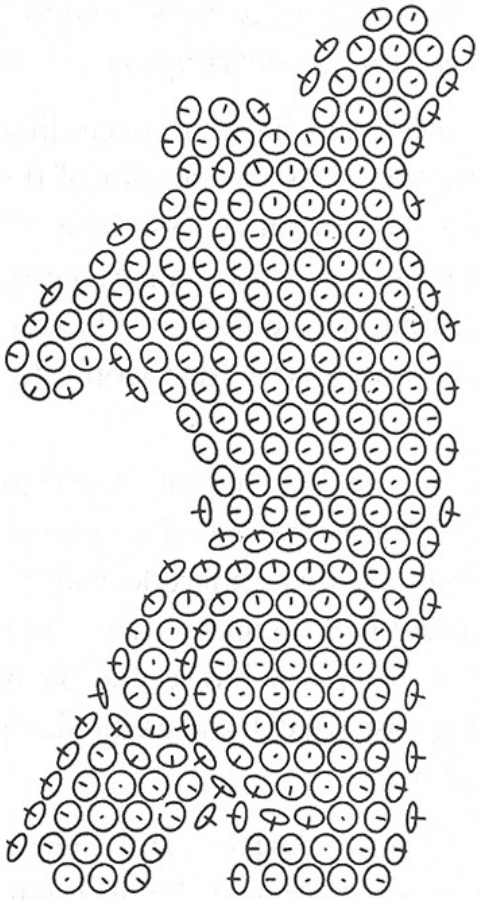
- The percentage changes in image luminance are directly proportional to percentage changes in the orientation of the surface.
- It only computes the angle between the incident light and the surface normal.
- The percentage changes in image luminance are to determine the absolute orientation of the surface, there must be some points of known orientation to anchor the computation.
  - Terminator boundaries:



Perceiving surface orientation from shading

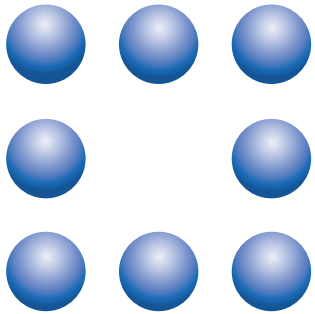
The surface orientation can easily and accurately be perceived as circles oriented in depth, at a particular slant and tilt, with short lines sticking perpendicularly out of their centers.



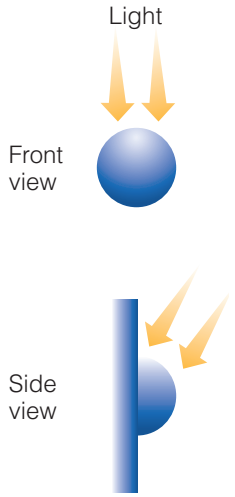


(a) Early morning shadows emphasize the mountain's contours.
(b) When the sun is overhead, the shadows vanish, and it becomes more difficult to see the mountain's contours.

- Heuristic assumption: our visual systems implicitly assume that illumination comes from above.



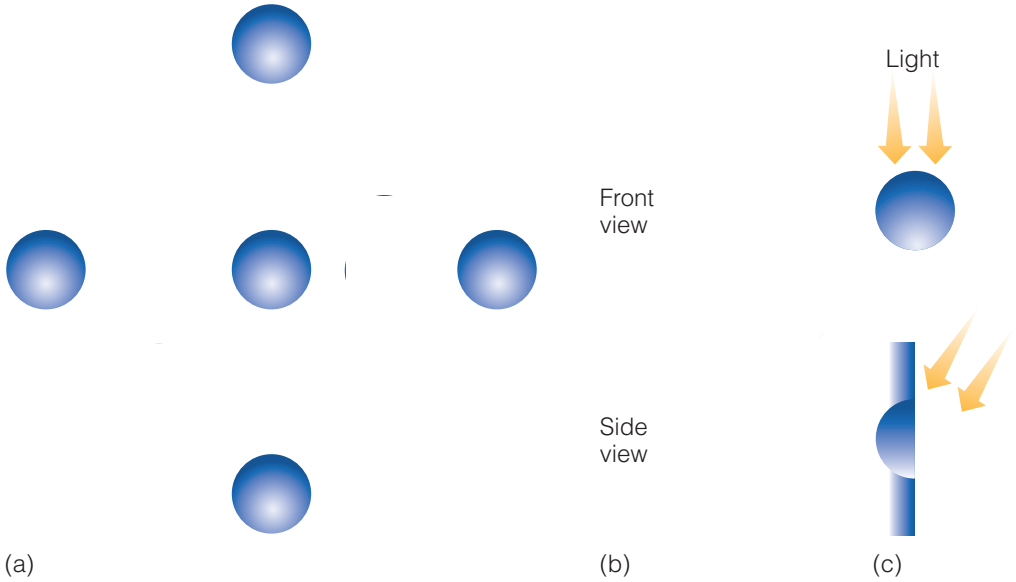
(a)



(b)

- Because our visual environment almost always is illuminated from above.

- Heuristic assumption: our visual systems implicitly assume that illumination comes from above.



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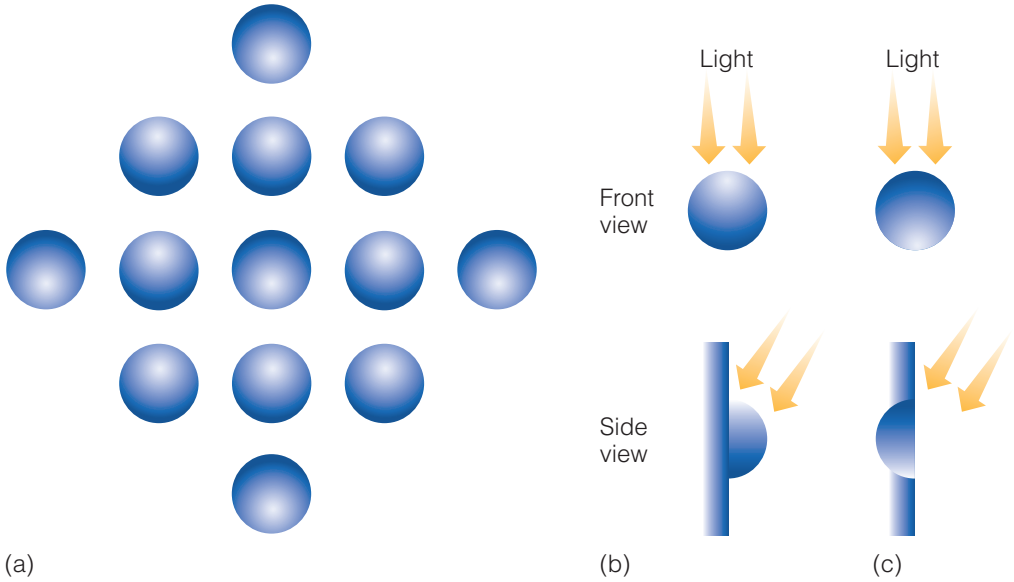

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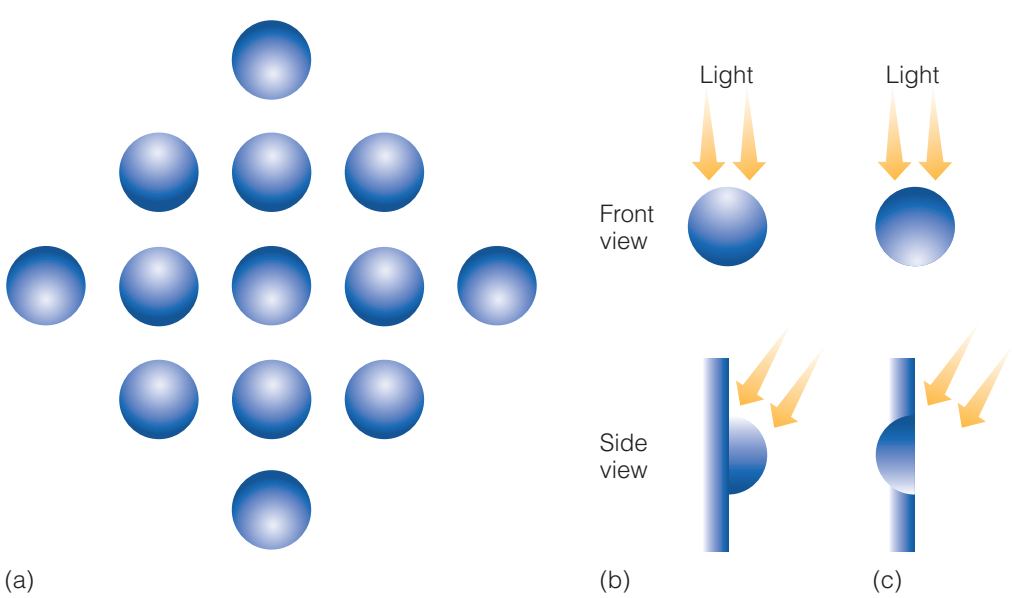
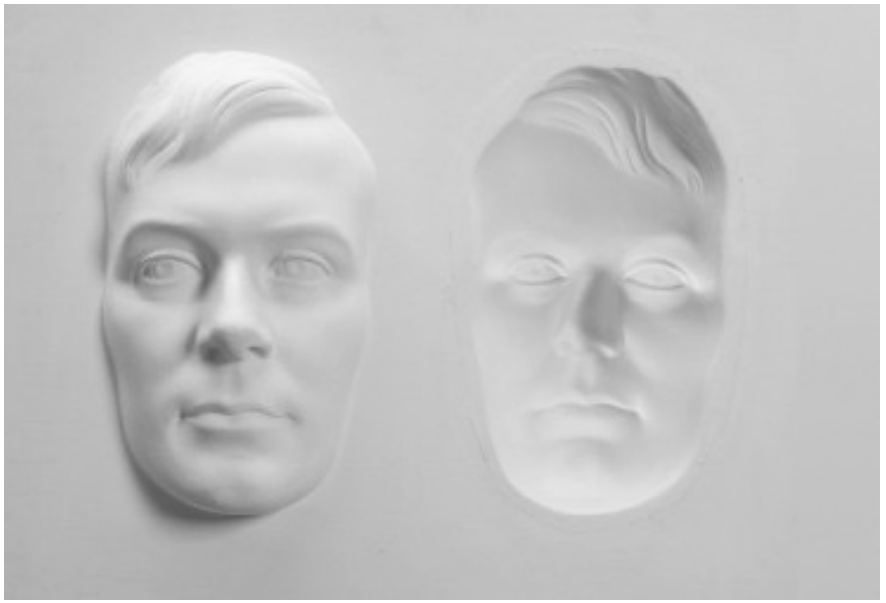
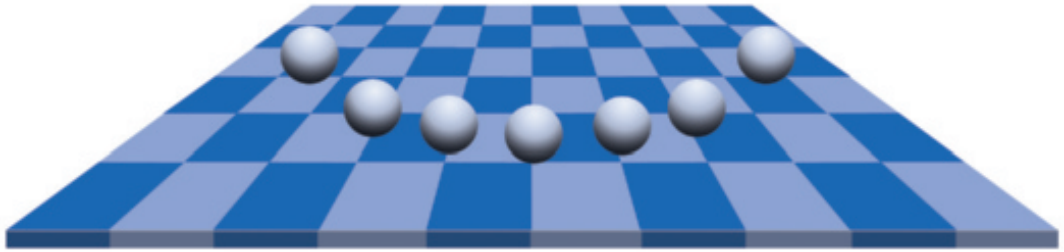




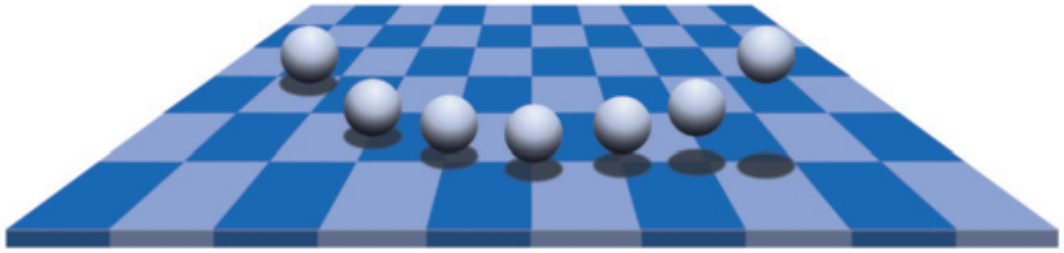
- Because our visual environment almost always is illuminated from above.

Cast shadows

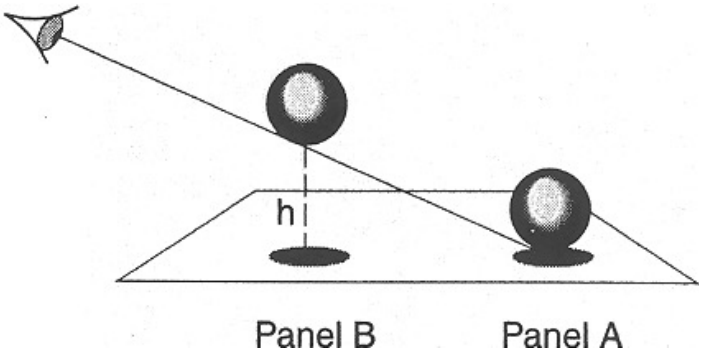
- **Cast shadows**: shadows of one object that fall on the surface of another object.



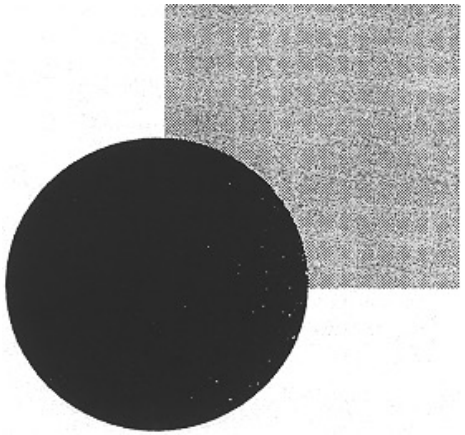
(a)



(b)



5.8 Edge interpretation

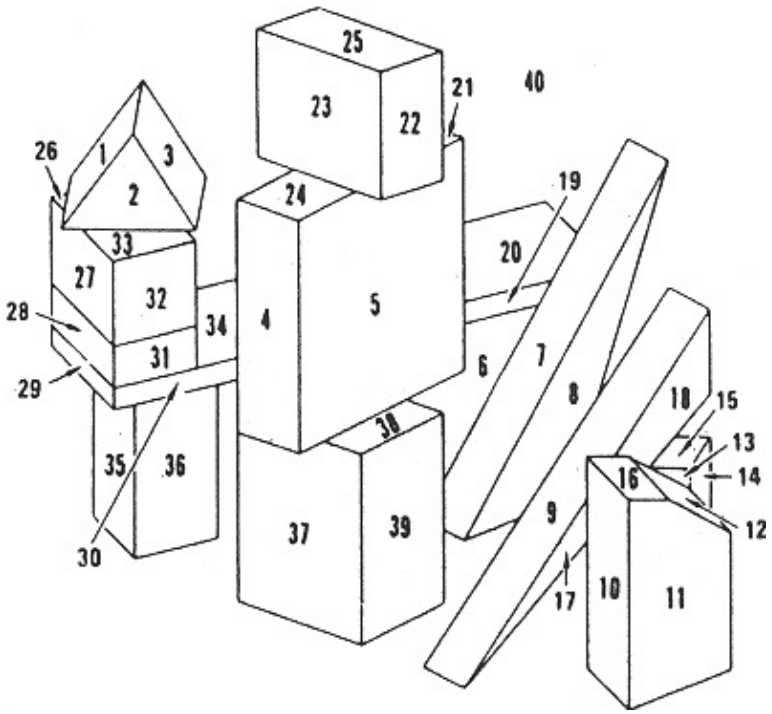


- **Occlusion**: the blocking of light from an object by an opaque object nearer the viewer.
- **Weak**: relative rather than absolute, qualitative rather than quantitative. Edge specifies only ordinal depth relations, but can not how much farther.
- **Strong**: available from virtually unlimited distances, provided that the objects be within visible range and that the closer one be opaque.

- ***How*** depth information arises from edges in 2-D images and ***how*** our visual systems might extract it.

- The ***goal of edge interpretation*** is to determine the best interpretation for all edges in a line drawing of a blocks-world scene.
  - Edges can arise in an image in several different ways.
  - The output of an edge interpretation program is a classification of the edges in terms of their environmental sources.

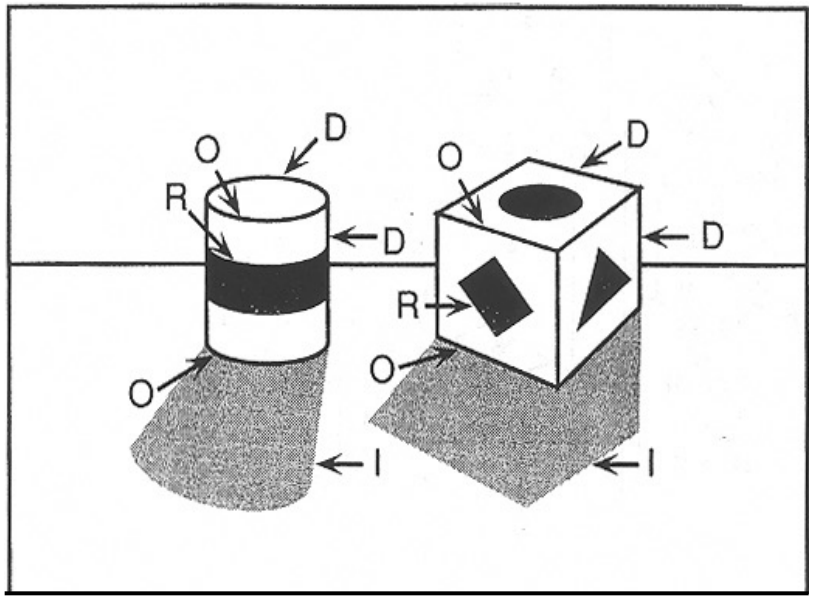
Vertex classification



- Vertices (junctions): the intersections of edges, which were crucial to determining what edges were occluded by what others.
- Vertex types: T's, Y's, K's, X's, L's, and so forth.
- The local constraints at each vertex and their interrelations reduced the number of possible interpretations of each edge.

Four types of edges

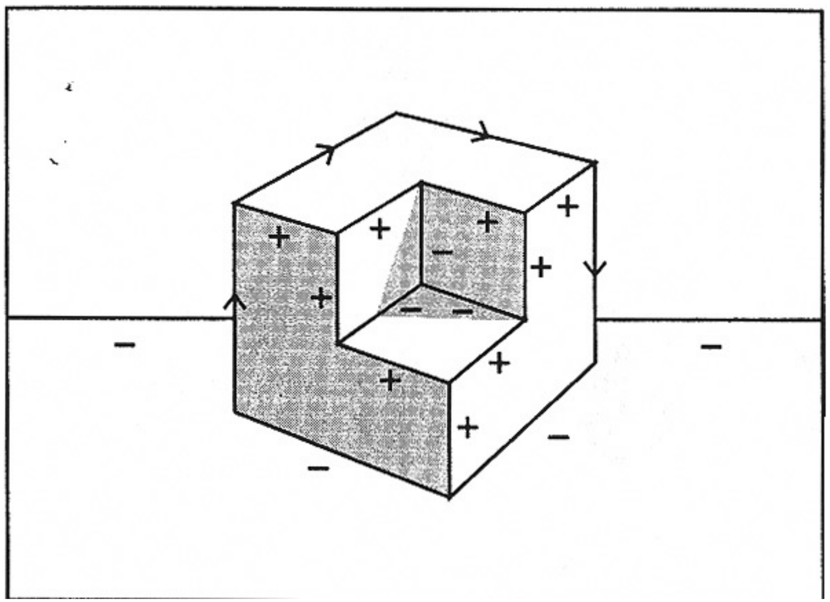
- The edges: meaning discontinuities in image luminance.
- The task is to interpret the edges in terms of the environmental situation.



- Four types:
  - ***Orientation edges***: discontinuities in surface orientation.
  - ***Depth edges***: a spatial discontinuity in depth between surfaces
  - ***Illumination edges***: difference in the amount of light falling on a surface.
  - ***Reflectance edges***: changes in the light-reflecting properties.

Edge labels

- Each edge is either an **orientation edge** or a **depth edge**, and can be unambiguously labeled as one or the other.

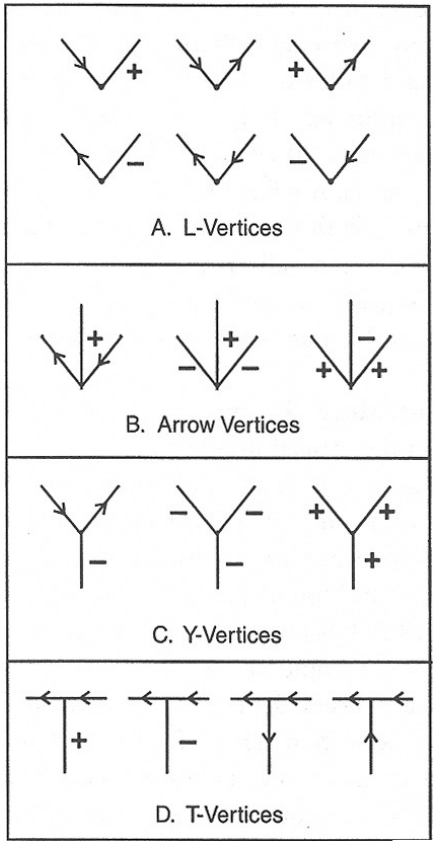


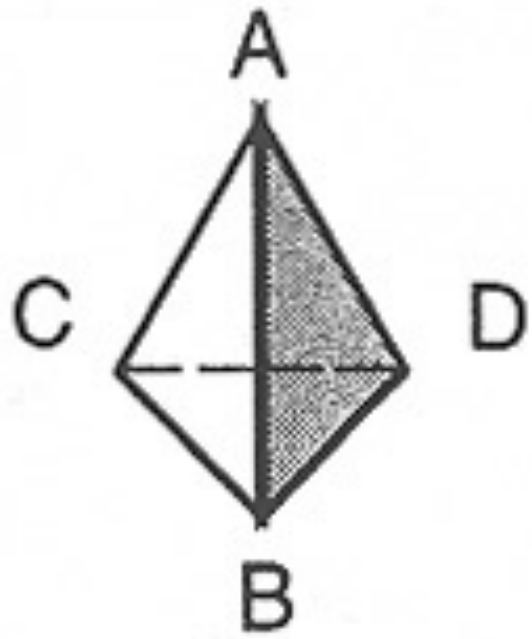
- Two types of orientation edges:
  - ***Convex orientation edges***: a dihedral angle of less than 180 degree."+"
  - ***Concave orientation edges***: a dihedral angle of more than 180 degree."-"
- Two cases of depth edges:
  - ***Right-hand rule***:

- If there are n edges in the drawing, there are 4^n logically possible labelings for it.

Physical constraints

- There are 4^3 logically possible labelings for an arrow junction. But only three of them are physically possible.
- Polyhedra with planar surfaces—each edge has a constant interpretation along its entire length.





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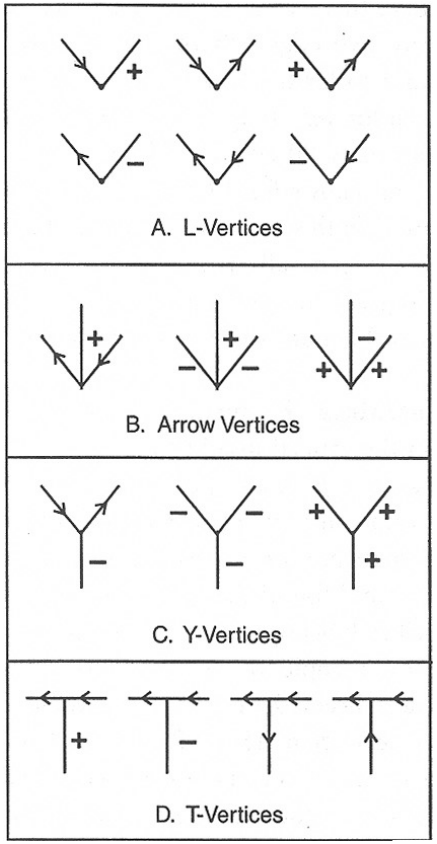
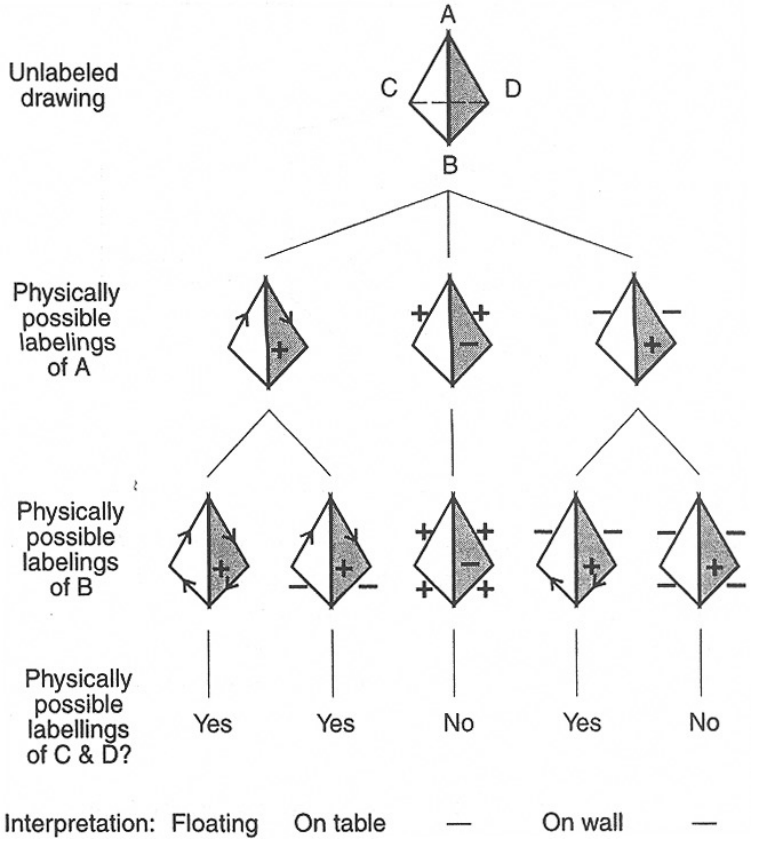
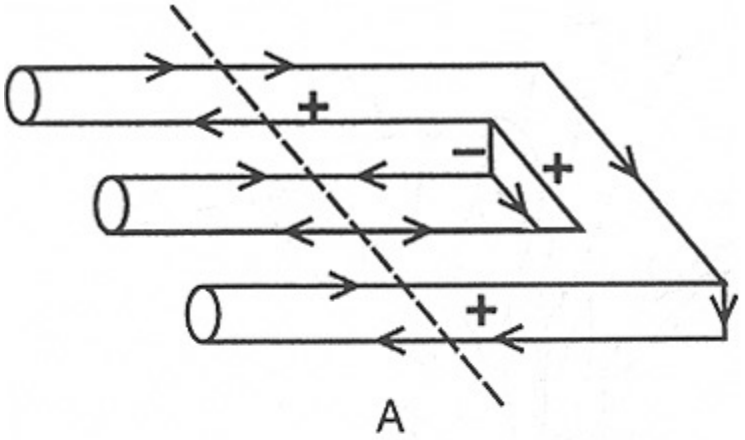
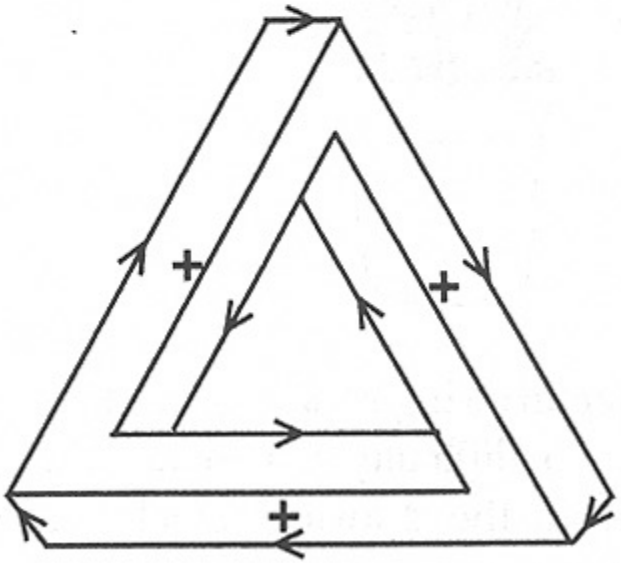




- Impossible objects:
  - Some objects cannot be consistently labeled.
  - Some objects do have consistent labelings.



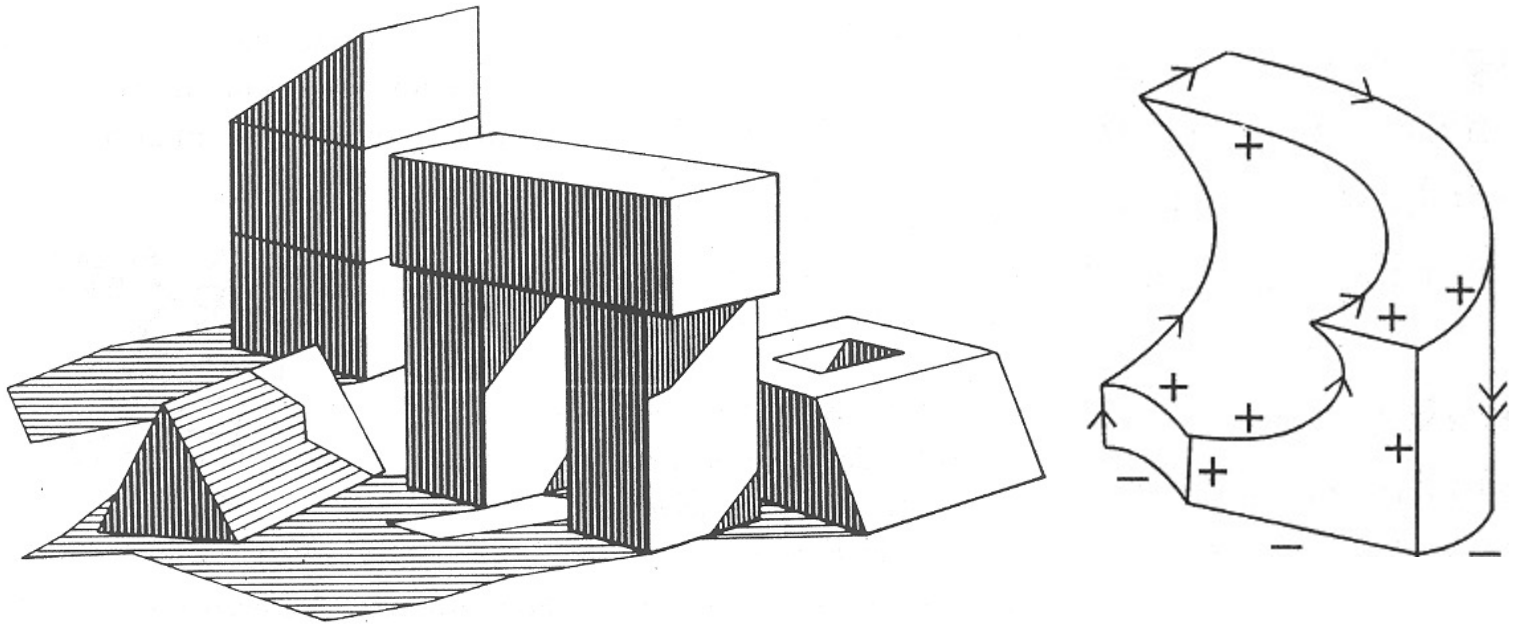
A



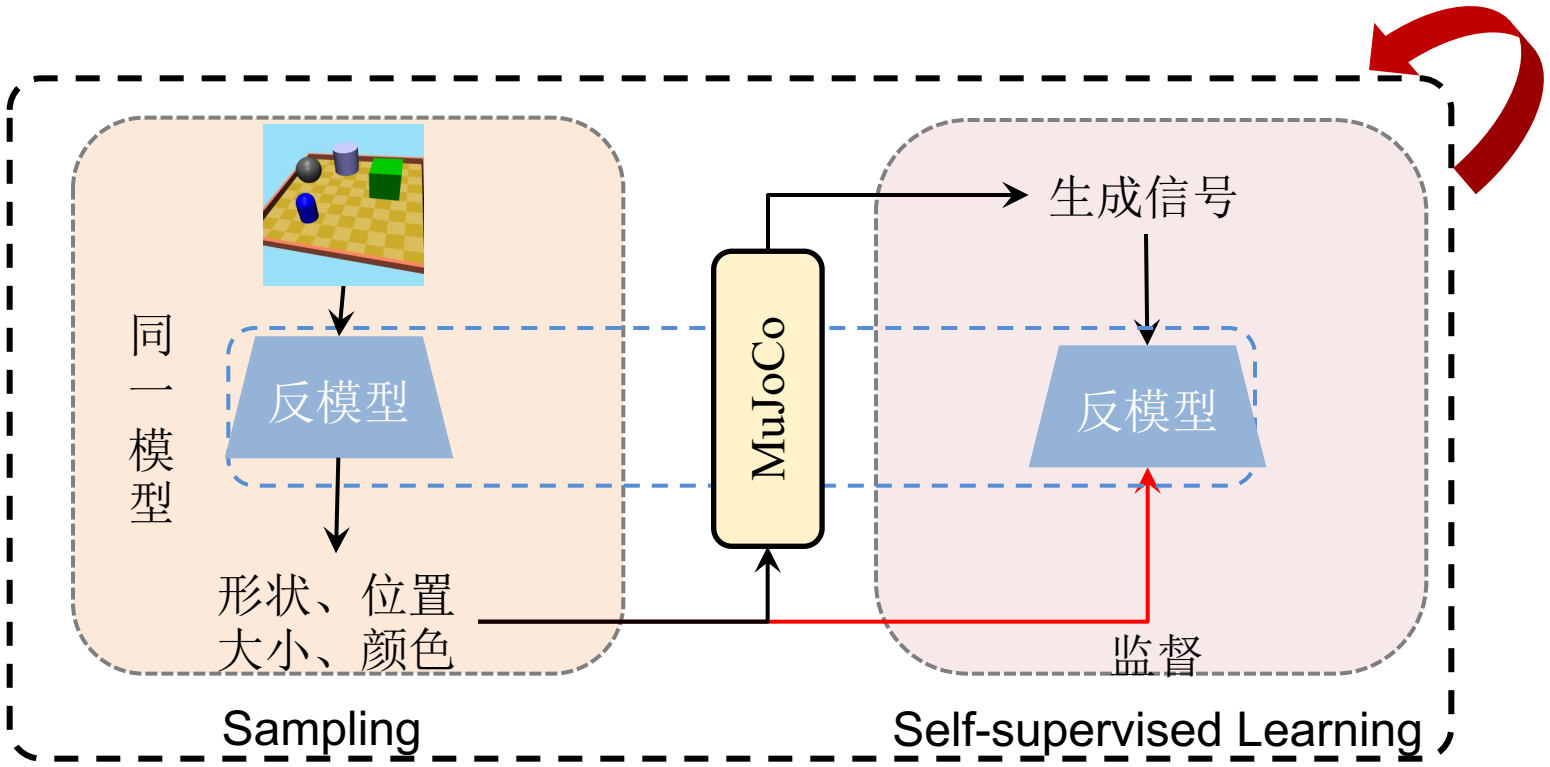
B

Extensions and generalizations

- Waltz extended the above analysis to include **11 types** of edges, including shadows and cracks. It turned out to reduce even further the number of possible interpretations.

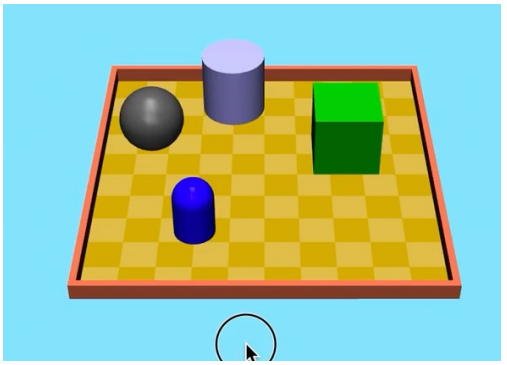


Combined Top-down and Bottom-up Processes



3D Results

形状	位置(x,y,z)	大小	颜色(R,G,B)
cylinder	(2, 7, 2.0)	(2.0, 2.0)	(0.67, 0.67, 1.0)
capsule	(4, -5, 1.2)	(1.2, 1.2)	(0.0, 0.0, 1.0)
sphere	(7, 3, 2.0)	(2.0)	(0.33, 0.33, 0.33)
box	(5, 2, 2.0)	(2.0, 2.0, 2.0)	(0.0, 0.67, 0.0)



Sources of information about depth

	INFORMATION SOURCE	Ocular/ Optical	Binocular/ Monocular	Static/ Dynamic	Relative/ Absolute	Qualitative/ Quantitative
Ocular	Accommodation	ocular	monocular	static	absolute	quantitative
	Convergence	ocular	binocular	static	absolute	quantitative
Stereoscopic	Binocular Disparity	optical	binocular	static	relative	quantitative
Dynamic	Motion Parallax	optical	monocular	dynamic	relative	quantitative
	Texture Accretion/Deletion	optical	monocular	dyanmic	relative	qualitative
Pictorial	Convergence of Parallels	optical	monocular	static	relative	quantitative
	Position relative to Horizon	optical	monocular	static	relative	quantitative
	Relative Size	optical	monocular	static	relative	quantitative
	Familiar Size	optical	monocular	static	absolute	quantitative
	Texture Gradients	optical	monocular	static	relative	quantitative
	Edge Interpretation	optical	monocular	static	relative	qualitative
	Shading and Shadows	optical	monocular	static	relative	qualitative
	Aerial Perspective	optical	monocular	static	relative	qualitative

Range of Effectiveness of Different Depth Cues

DEPTH INFORMATION	0–2 METERS	2–20 METERS	ABOVE 30 METERS
Deletion and accretion	✓	✓	
Occlusion	✓	✓	✓
Relative size	✓	✓	✓
Accommodation and convergence	✓		
Motion parallax	✓	✓	
Relative height		✓	✓
Atmospheric perspective			✓

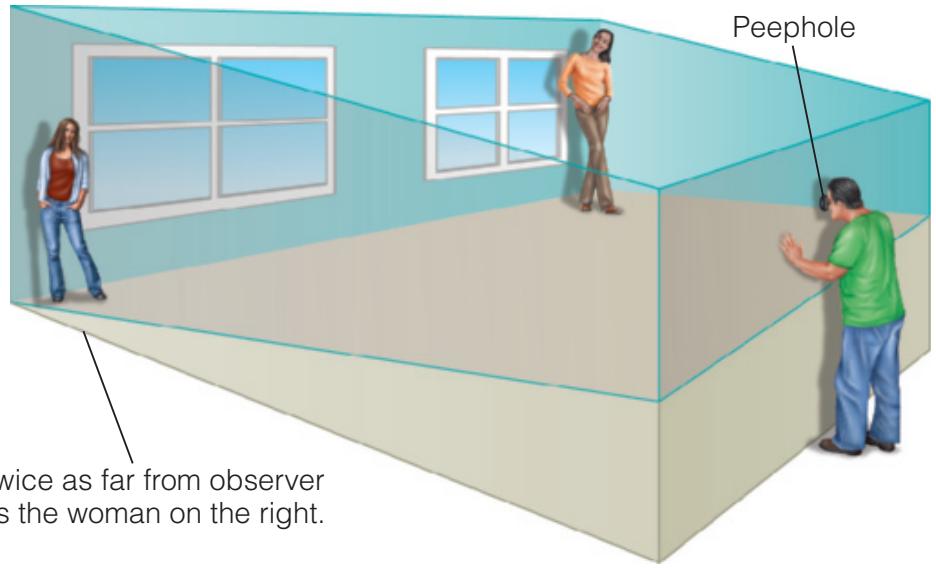
6 Integrating information sources

- Since all the sources of depth information bear on the same perceptual interpretation of surfaces oriented in depth, they must be put together into a coherent consistent representation.
- ***How does the visual system accomplish this integration***?
  - Under normal viewing conditions, unproblematic.
  - In the laboratory, different factors can be manipulated independently so that cues come into conflict, ***which may imply about the rules for integrating different sources***.

6.1 Dominance

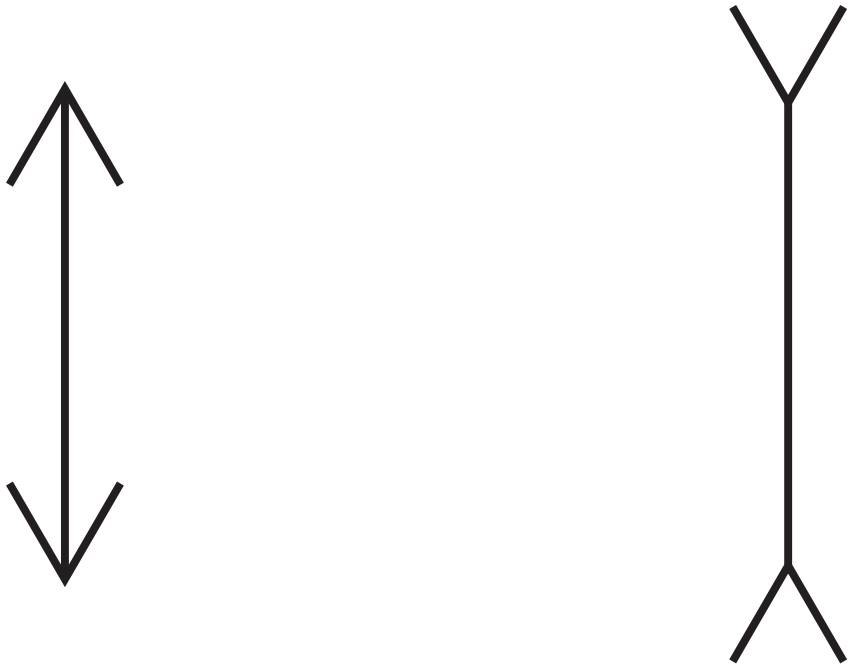
- One information source will dominate some other conflicting source with the result that the latter is completely ignored.
- This implies a hierarchy of depth sources such that those higher in the ordering dominate those lower down.

Ames room

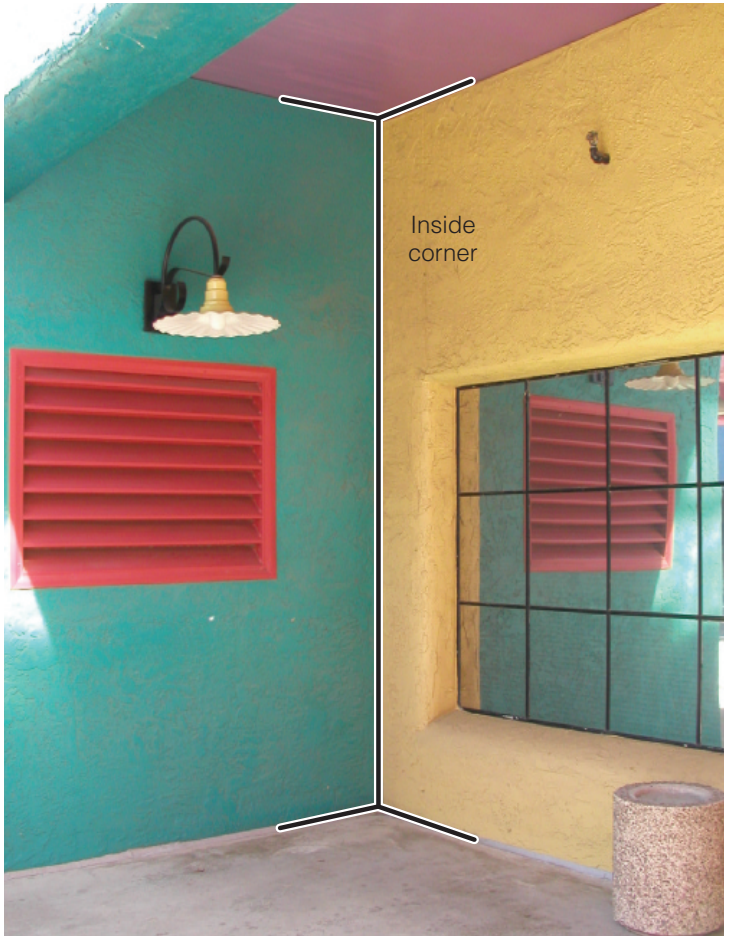


- Two illusions
  - The people are seen as equally distant
  - They are seen as differing greatly in size
- ***Familiar size information is overwhelmed by the evidence from perspective***.

The Müller-Lyer illusion

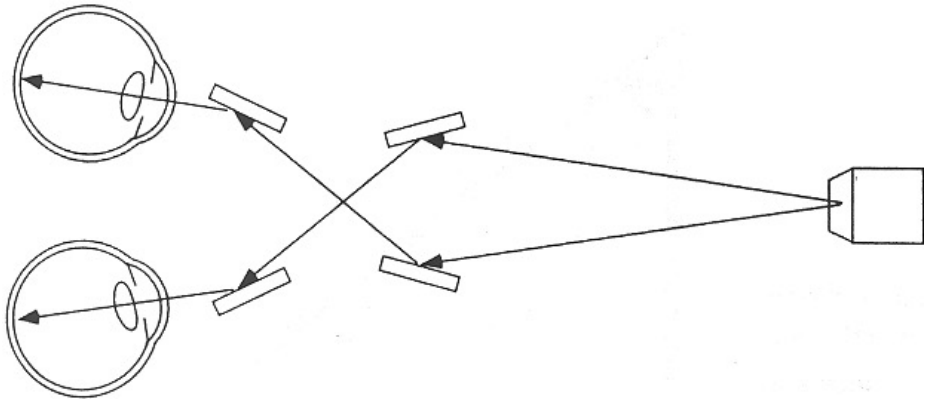


Both lines are actually the same length.



Misapplied Size Constancy Scaling (According to Gregory, 1966)
The Müller-Lyer line on the left corresponds to an outside corner, and the line on the right corresponds to an inside corner.

- **Pseudoscope**: An optical device reverses binocular disparity simply by reversing the images that are projected to the left and right eyes.



- The instrument reverses the horizontal disparities of everything
  - Objects that are closer should appear farther.
  - Convex objects should appear concave.
- If a complex normal scene is viewed, its depth does not reverse.
- ***Disparity information can be overridden by monocular pictorial information***, such as occluding edges, texture gradients, perspective, and prior knowledge.

6.2 Compromise

- The visual system may integrate information from different sources by finding compromise solutions that are consistent with neither source alone but fall somewhere in between.
  - Example: experiment (relative size, position relative to the horizon, occlusion, and motion parallax)
- The **basic idea:**
  - Many different estimates of depth may be computed independently and in parallel, each producing a different estimate of depth at each point in a depth map.
  - The multiple depth maps are then integrated by averaging, adding, multiplying, or other combination rules.
- **Weak fusion**: it assumes no interaction between different information sources.

6.3 Interaction

- It seems quite likely on a priori grounds that different kinds of depth information from different modules are not kept separate, but interact, at least to some degree, in arriving at a single coherent representation of the distance to visible surfaces.
  - Relative / absolute depth
- **Modified weak fusion**: that allows for certain limited kinds of interactions among depth sources.
- ***This is one of the least understood topics in the perception of surface layout.***

Summary

- Patch(orientation, distance) → depth
- Ocular information
- Stereoscopic information
- Dynamic information
- Pictorial information
- Integrating information sources

Question?