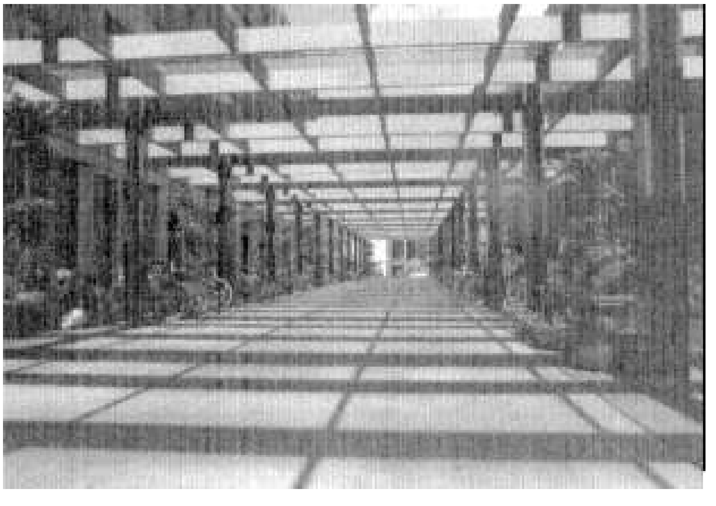
Pictorial Information

- Although stereopsis and motion produce particularly compelling experiences of depth, they are not the only sources of depth information.
- If you close one eye and keep your head still, the world continues to look quite three-dimensional.
- Another is that photographs and certain kinds of realistic drawings and paintings can produce compelling impressions of depth.
- See example.



A demonstration of pictorial sources of depth information.
This photograph contains a great deal of optical information about depth that arises from stationary, monocular structure in the image.

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Pictorial Information

- The remaining sources of depth information are known collectively as pictorial information because they are all potentially available in static, monocularly viewed pictures.
- Pictorial information can be very powerful, for it often leads to good depth perception in 2-D pictures when both stereo and motion information indicate that they are quite flat.
- Indeed, it can even overcome stereo depth information.

Familiar Size

- Many objects have a characteristic size or range of sizes with which experienced perceivers are familiar.
- Vast majority of adult men vary between 5 feet 6 inches and 6 feet 2 inches.
- If the size of an object is known to the perceiver, then the size-distance relationship can be used to obtain its actual distance from the observer.

Familiar Size

- The knowledge involved here is not conscious knowledge, nor is solving the equation deliberate symbolic manipulation. Rather, they are rapid, unconscious processes that occur automatically, without our even thinking about them.
- See example.

Relative size as a cue to depth.
The cheerleaders in this line are all about the same size, but their projected images become smaller as their distances from the camera increase. If one assumes that they are actually about the same size, their relative distances can be recovered from their image sizes.

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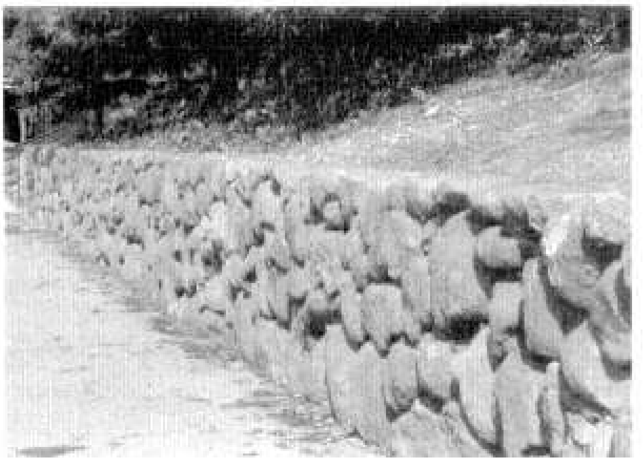
Texture Gradients

- Texture gradients is the systematic changes in the size and shape of small texture elements that occur on many environmental surfaces.
- See example.
- Complex surface shapes can be realistically depicted by textural variations.
- See example.



Natural texture gradients.
Many natural surfaces are defined by texture elements of about the same size and shape so that surface depth and orientation can be recovered from systematic changes in their projected sizes and shapes.

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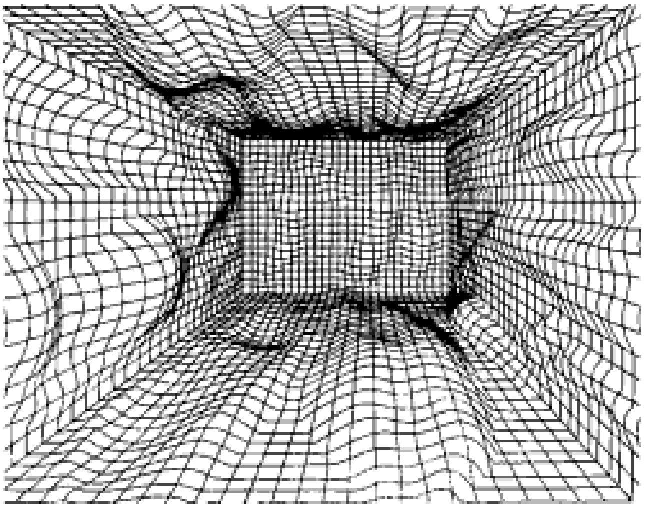

Artificial texture gradients.
Artificial surfaces of arbitrarily complex shapes can be rendered by using identical texture elements in computer graphic displays.

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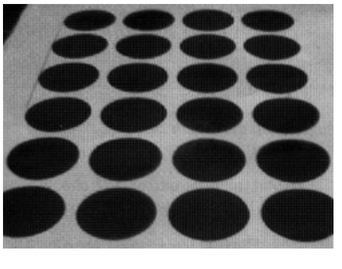
Texture Gradients



The overall size of texture elements diminishes with distance as distance to the texture elements increases.

Thus size gradient can be used to estimate the relative distance to different parts of the surface and thus to recover the orientation of the surface.

Density gradient can also be used to recover orientation.

Texture Gradients

- This will be true only if the texture elements are actually about the same size. This is called the homogeneity assumption.
- This is another example of heuristic assumptions in depth perception.
- If the texture elements are not similar in size, then illusions of depth and surface orientation will result.

Texel Shape

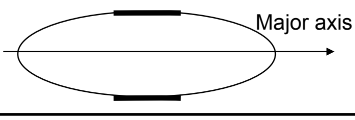
- The projected shape of texture elements can also carry information about the orientation of the surface.
  - E.g. circle becomes ellipse (foreshortening effect)

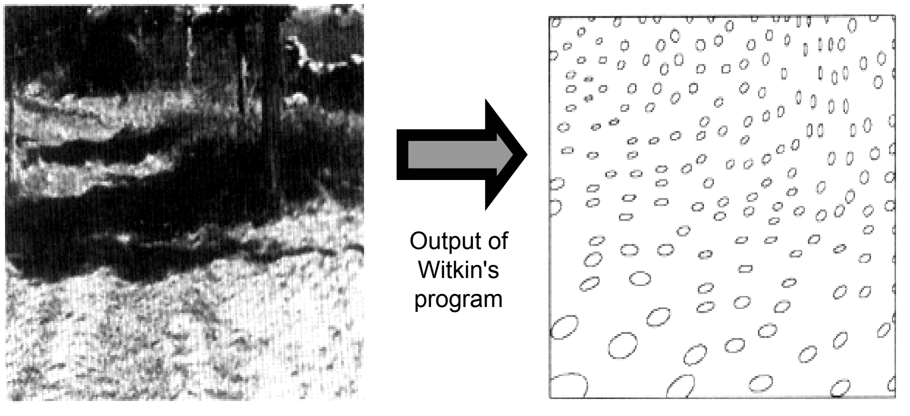
This only works if additional assumptions are made about the actual shapes of the texture elements.

1. Physical texture doesn't mimic foreshortening. Leaves? Grass? Tree bark?
2. Texel is planar. Ocean waves? Pebbles? Grass?

Texel Shape

- Witkin (1981) proposed an algorithm based on the assumption that the amount of contour (arc length) at different orientations will be approximately the same (Isotropic assumption).
- This is a useful heuristic because when isotropic texture elements are viewed at a slant, their edges will not be isotropic in the image plane.
  - Eg circle becomes ellipse, where the distribution of arc length have a maxima & a minima at the major & minor axis respectively.
  - The direction of min coincides with the tilt direction. Relative height of the peaks define the amount of slant.
- See example.





A B

Estimating local surface orientation from texture.
Panel A shows a natural scene that includes significant texture information, and panel B shows the output of Witkin's program in which the shape and size of the ellipses convey the estimated depth and orientation of the local regions of surface. (From Witkin, 1981.)

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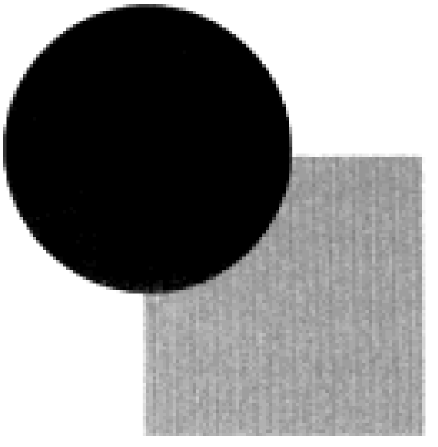
Edge Interpretation

- One very important class of pictorial information about depth comes from the interpretation of edges or contours.
- See diagram.
- What is present is a 2-D configuration of regions bounded by edges.
- Yet we perceive these edges as indicating a depth relation: The circle is in front of the square.



Partial occlusion as depth information.
When one object partly occludes another, the occluding object is perceived as closer and the occluded object as farther.

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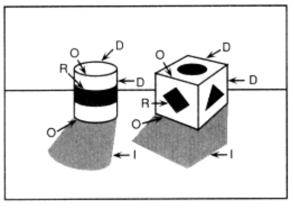
Edge Interpretation

- A sophisticated theory of edge interpretation has evolved within computer vision in the **block world** environment.
- Edges can arise in an image in several different ways. The task is to interpret them in terms of the environmental situation that produced them.
  - Such distinctions are important for pictorial depth information because some edge interpretations imply specific depth relations.

Four Types of Edges

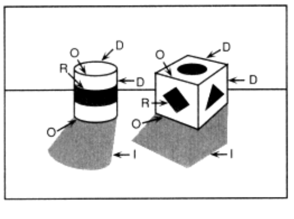
- There are four types of edge interpretations:
  - Orientation edges
  - Depth edges
  - Illumination edges
  - Reflectance edges

Orientation edges



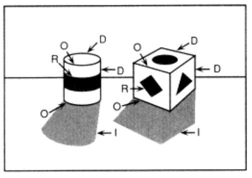
- Orientation edges refer to places in the environment in which there are discontinuities in surface orientation.
- These occur when two surfaces at different orientations meet along an edge in the 3-D world.
- Examples of orientation edges are labeled with O's.

Depth edges



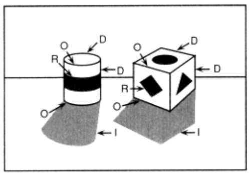
- Depth edges refer to places where there is a spatial discontinuity in depth between surfaces.
- If they actually touch along the edge, then it is classified as an orientation edge.
- Examples of depth edges are labeled with D's.

Illumination edges



- Illumination edges are formed where there is a difference in the amount of light falling on a homogeneous surface, such as the edge of a shadow, highlight, or spotlight.
- Examples of illumination are labeled with I's.

Reflectance edges



- Reflectance edges result where there is a change in the light - reflecting properties of the surface material.
- The most obvious examples are when designs are painted on an otherwise homogeneous surface.
- Examples of reflectance are labeled with R's.

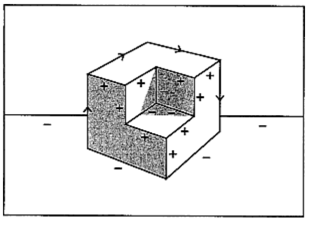
Edge Labels

- We will focus on orientation and depth edges because these edges provide the strongest constraints on depth interpretations of the scene.
- We therefore begin with a line drawing that contains only orientation and depth edges
- Orientation and depth edges in objects with flat surfaces are mutually exclusive.
  - Each edge in the line drawing is therefore either an orientation edge or a depth edge

Edge Labels

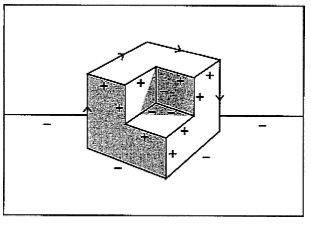
- We need to further differentiate the labeling system so that there is a unique label for each qualitatively different type of orientation and depth edge.
- Two kinds of orientation edges and two kinds of depth edges are required.
- Two kinds of orientation edges:
  1. convex
  2. concave
- They carry important information about the depth of the edge relative to the surfaces.

Convex orientation edges



- They occur when two surfaces meet along an edge and enclose a filled volume corresponding to a dihedral (two-faced) angle of less than 180°.
- Convex edges indicate that the edge's angle points toward the observer, as do the external edges of a cube seen from the outside.
- Convex edges are illustrated by the lines labeled with a "+."

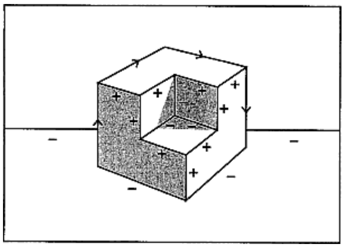
Concave orientation edges



- They occur when two surfaces meet along an edge and enclose a filled volume corresponding to a dihedral angle of more than 180°.
- Concave edges indicate that the edge's angle points away from the observer, as do the internal edges of a hollow cube seen from within.
- Concave edges are illustrated by the lines labeled with a "-."

Edge Labels

- There are also two cases of depth edges that need to be distinguished:
  - one in which the occluding surface is on one side of the edge, and vice versa.



Depth edges are labeled by single arrowheads running along the edge, and the convention for its direction is a right-hand rule:

-- The arrow is placed facing in the direction along which the closer, occluding surface is on the right side of the edge.

Edge Labels

- These two possible labels for each depth edge — an arrow in one or the other direction along the edge — are mutually exclusive, since the occluding edge can be on only one side.
- The correct labeling carries important depth information because it designates which surface is closer to the observer.

Edge Labels

- Thus, there are four possible labels for each edge in a line drawing containing only orientation and depth edges, all of which contain significant depth information.
- This means that if there are **n** edges in the drawing, there are $4^{\mathbf{n}}$ logically possible labelings for it, corresponding to $4^{\mathbf{n}}$ qualitatively different depth interpretations.
- This is an very large number even for very simple scenes! (4^{20} =1,048,576)

Physical Constraints

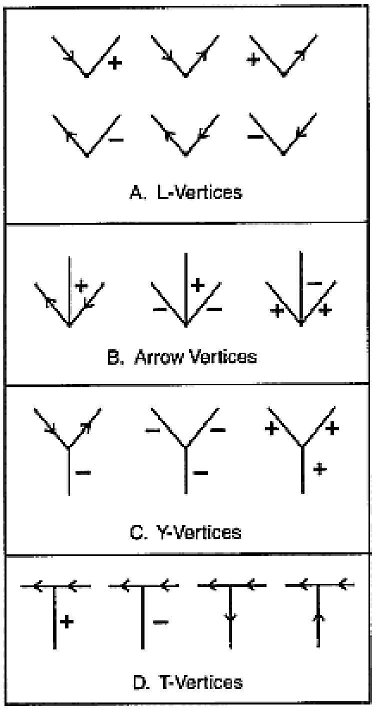
- But in most other cases, people generally perceive just one. How is that possible?
- Huffman and Clowes based their analyses on the crucial insight that not all possible labelings are physically possible.
- They examined local constraints at vertices of trihedral objects—objects whose corners are formed by the meeting of exactly three faces—and found that only a small fraction of possible labelings could be physically realized.

Physical Constraints

- Consider a set of possible "arrow" junctions, in which three edges meet at an angle in the image plane of less than 180°.
- Because each edge could be labeled in any of the four ways described above — as a concave or convex orientation edge or as a right-handed or left-handed occluding edge — there are 4^3 (= 64) possible labelings for an arrow junction.

Physical Constraints

- However, Huffman and Clowes proved that only three of them are physically possible.
- The same reduction of 64 to 3 possibilities is achieved for "Y" junctions.
- <u>See diagram.</u>



The catalog of vertex types for trihedral angles. All physically possible interpretations of vertices are shown for "L," "arrow," "Y," and "T" vertices.

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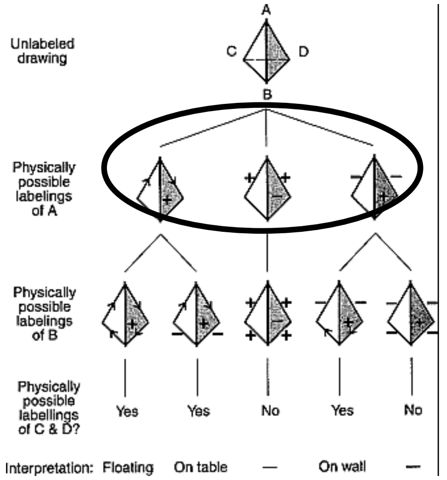
Physical Constraints

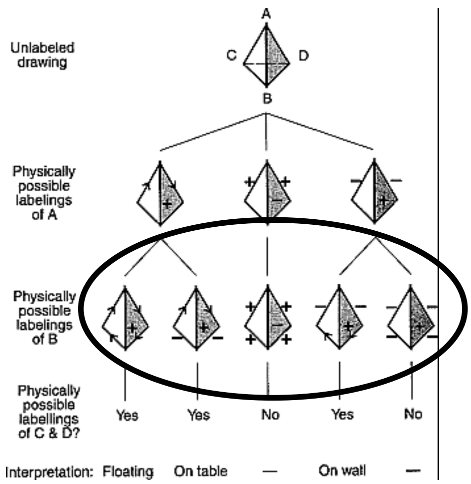
- There are further constraints on edge interpretation that operate at a more global level.
- Within the constraints of the objects in blocks world each edge has a constant interpretation along its entire length.
  - Convex edges cannot become concave.
  - Right-handed occluding edges cannot become left-handed.
  - Unless there are vertices between the edges that allow the change in interpretation.
- The number of possible labelings can be further reduced.

Physical Constraints



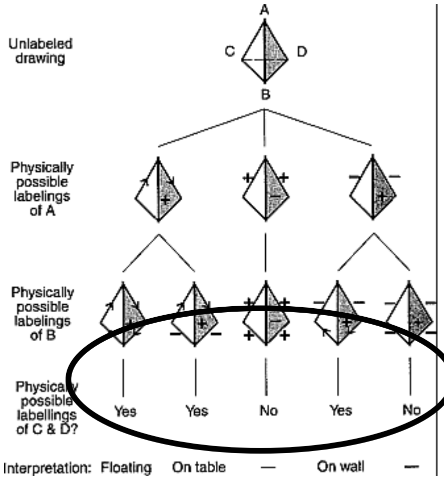
- Consider all physically possible labelings of the arrow vertex A.
- From the diagram, we know that there are just the three shown.

Physical Constraints



- Next, consider how these possibilities interact with all physically possible labelings of the arrow vertex B.
- Of the nine possibilities, four are eliminated by physical constraints because they would require two different labels for the central edge.

Physical Constraints



- Finally, consider whether the resulting five labelings of vertices A and B provide physically possible labelings for the "L" junctions at vertices C and D.
- This constraint eliminates two more, leaving only three physically possible interpretations.

Physical Constraints

- What are these three interpretations?
  1. The perceptually preferred one has concave orientation edges at the bottom, as would be found if the tetrahedron were sitting with its lower surface (BCD) on a table.
  2. The alternative with concave orientation edges at the top corresponds to the percept of the tetrahedron attached to a wall by its back surface (ACD).
  3. The one with occluding depth edges all along the perimeter corresponds to a tetrahedron floating unsupported in the air.

Physical Constraints

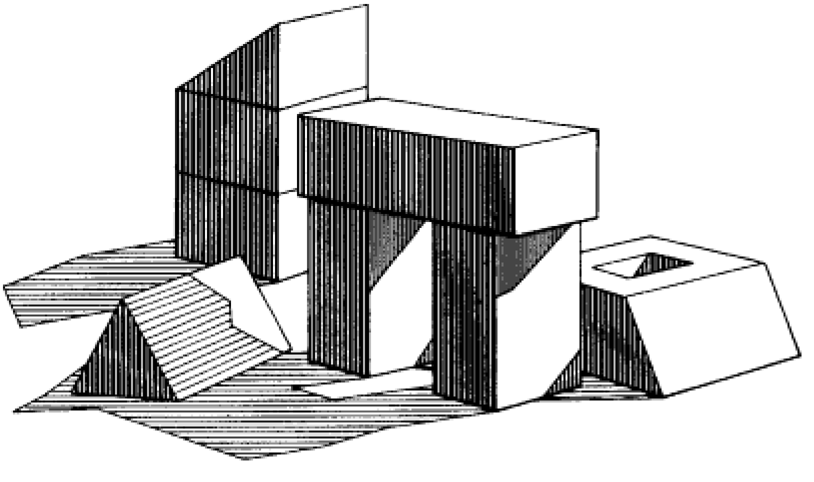
- Notice how drastically the set of possible labelings was reduced by imposing physical constraints.
- We began with a five-line drawing that could have 4^5 (= 1024) possible labelings and only three remained!
- Notice that this edge analysis does not provide any way to decide among these three alternatives.
- And so further constraints must be introduced to settle on a single solution.

Extensions and Generalizations

- The Huffman-Clowes analysis of physical constraints was a major conceptual breakthrough in the theory of edge interpretation.
- David Waltz (1975) extended the Huffman-Clowes analysis to include 11 types of edges, including shadows and "cracks" (lines that result from the exact alignment of coplanar edges: essentially, orientation edges at 180° angles).

Extensions and Generalizations

- This expansion of edge types increase the catalog of physically possible vertices to thousands of entries.
- But by extrapolating the conclusions of the Huffman-Clowes analysis, it reduces the number of possible interpretations that could be assigned to a given shaded line drawing even further.
- See example.



A blocks world scene with shadows.
Waltz's algorithm for edge interpretation produces just one interpretation for this scene, which is the one people always perceive. Adding shadows makes the interpretation process more accurate because it provides further constraints.

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Extensions and Generalizations

- The success of Waltz's algorithm for assigning edge interpretations does not even approach human levels of competence.
- Because its application is limited to planar polyhedra.
- It does not work for curved surfaces or for objects that contain thin sheets (such as folded paper) rather than volumes.

Extensions and Generalizations

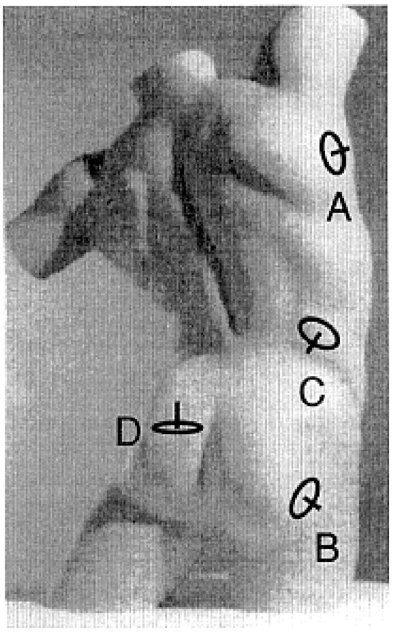
- Neither of these pose serious problems for human observers, who can interpret line drawings of scenes involving quite complex objects of either type.
- On the other hand, Waltz's program is uncanny in its ability to arrive at physically possible interpretations, some of which people seldom perceive.

Shading Information

- Another useful and effective source of information about the shape of surfaces curved in depth comes from shading:
  - variations in the amount of light reflected from the surface as a result of variations in the orientation of the surface relative to a light source.
- A difficult computational problem due to the physics involved in light reflectance, and the resulting PDE equations.

Perceiving Surface Orientation from Shading

- Koenderink, Van Doorn, and Kappers (1992, 1996) studied the ability of human observers to recover surface orientation and depth from shaded objects and pictures.
- They showed observers pictures of the <u>human torso</u> and had them indicate the perceived orientation of a fairly dense sampling of positions on the surface.
- Subjects were instructed to adjust each gauge figure so that it appeared to be a circle lying flat on the surface of the object with the line sticking perpendicularly out of the surface, as illustrated by ovals A and B in the photo.



Studying the perception of surface orientation from shading.

Subjects saw this picture of a male torso and adjusted the shape and orientation of oval test figures so that they looked like circles lying flat on the surface (A and B) rather than askew (C and D).

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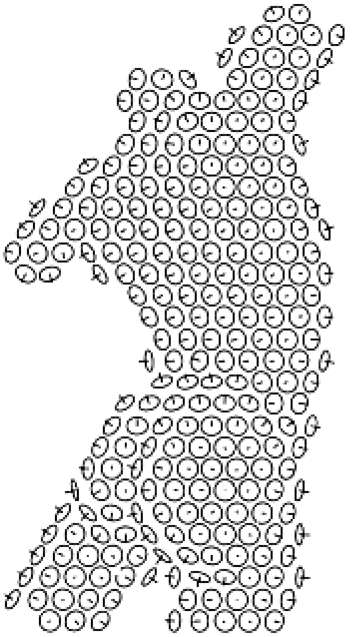
Perceiving Surface Orientation from Shading

- The results from one subject averaged over several sessions is shown here.
- Notice that this representation of the data approximates the appearance of the original torso in the texture gradient of many circles on its surface.



Local surface orientations reported by one subject.

The average ovals produced by one subject for every point tested on the surface of the male torso

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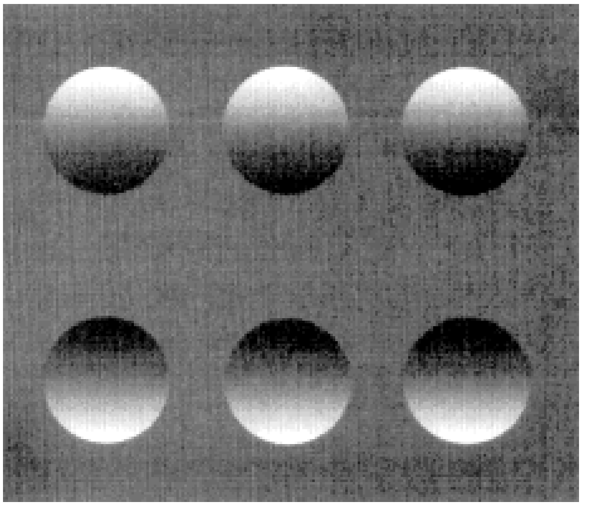
Perceiving Surface Orientation from Shading

- They found that different subjects were remarkably similar in their qualitative perception of these surfaces but differed quantitatively in the amount they perceived.
- Observers were not using strictly local information in making their responses, but were integrating over a substantial region of the object's surface.
- These conclusions were not dependent on the surface depicting a familiar object such as a torso because they obtained similar results using unfamiliar abstract sculptures.
- Exactly what perceptual process might have produced these global effects is not yet clear.

Perceiving Surface Orientation from Shading

- The visual analysis of shading often rests on heuristic assumptions. See diagram.
- The top ones typically appear to be convex bumps, bulging outward toward the viewer, and the bottom ones appear to be concave dents, curving inward away from the viewer.
- In fact, this perception is veridical only if the illumination comes from above. You can demonstrate this simply by turning the picture upside down. This reverses the assumed direction of illumination and thus reverses the perceived sign of curvature.
- The assumption of illumination from above makes a great deal of sense because our visual environment almost always is illuminated from above.



Direction of illumination and perceived convexity.
The top row looks like convex bumps and the lower row like concave dents because the visual system assumes that illumination comes from above. If you turn the book upside down, the perceived convexity of these elements reverses.

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Integrating Information Sources

- We have examined a large number of sources for perceiving depth in a scene.
- Since all these sources 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?

Integrating Information Sources

- Under normal viewing conditions, integrating different sources of depth information is largely unproblematic because they are very highly correlated.
- However, In the laboratory, different factors can be manipulated independently so that cues come into conflict.
- The simplest possibility is that one information source will dominate some other conflicting source with the result that the latter is completely ignored.
- This form of integration implies a hierarchy of depth sources such that those higher in the ordering dominate those lower down.

Integrating Information Sources

- A well-known example of what appears to be dominance between depth cues is the Ames room, which pits perspective information against familiar size of objects.
- The Ames room is a greatly distorted room that looks normal from one particular viewpoint.
- See example.
- Even though it is not rectangular, it looks rectangular from the designated viewpoint.

Conflicting information in an Ames room.
Perspective information and familiar size information conflict when people are seen in an Ames room, a distorted room that appears to be rectangular from a single viewpoint. Perspective information dominates, so the people are perceived as greatly different in size.

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Integrating Information Sources

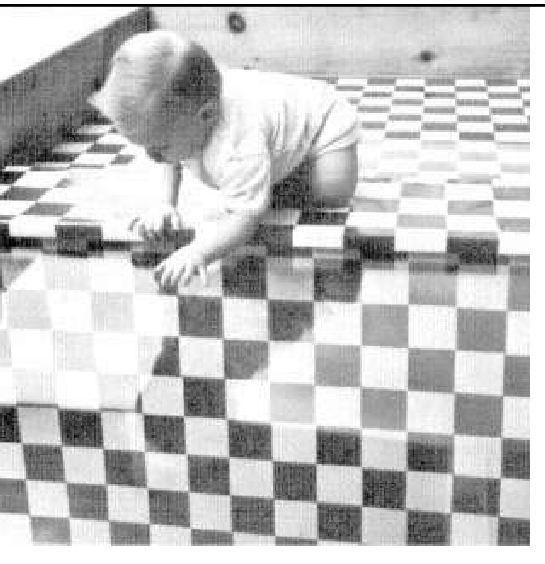
- Observers at the special viewpoint invariably report two illusions:
  - The people are seen as equally distant.
  - they are seen as differing greatly in size.
- Familiar size information suggests that the men are about the same size, but this possibility is overwhelmed by the evidence from perspective, which appears to completely dominate perception in this case.

Development of Depth Perception

- As adults we perceive the distance to surfaces and their orientations in space with no apparent effort.
- Is this
  - because we were born with the ability,
  - because it matured autonomously after birth, or
  - because we learned it and have become so well practiced that it has become automatic?
- Experiments with young children have begun to provide answers to this intriguing question.

Development of Depth Perception

- Some of the studies demonstrate that infants have functional depth perception early in life employed an apparatus called a visual cliff.
- See photo.
- Textured surfaces can be placed below the glass on either side of the central board at varying distances beneath it, and the lighting can be arranged so that the glass is essentially invisible.
- In the classic visual cliff experiment, Walk and Gibson placed a textured checkerboard surface directly below the glass on the "shallow" side and an identical texture on the floor, 40 inches below the glass on the "deep" side.



An infant on the visual cliff.
Infants are placed on the central board over a thick sheet: of glass that covers a textured surface on each side, one of which is shallow, lying just beneath the glass and the other of which is deep. When beckoned by their mothers, most infants will cross the shallow side, but few will cross the deep side.

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Development of Depth Perception

- The baby's mother was asked to put her child on the central board and to try to entice the baby to crawl across either the shallow side or the deep side.
- If the baby is able to perceive the distance to the two textured surfaces, it should be willing to crawl to its mother over the shallow side but not over the visual cliff.

Development of Depth Perception

- Of the 36 children tested from ages 6 to 14 months, 27 could be persuaded by their mothers to leave the central board.
- Of these, all 27 crawled across the shallow side at least once, whereas only three attempted deep side.
- This result shows that by the time babies can crawl at age 6 to 12 months, they have functional depth perception.

Development of Depth Perception

- To find out whether babies who are too young to crawl perceive depth, the heart rates of infants as young as two months old on a visual cliff apparatus were recorded.
- It was found that when two- to five-month-old infants were placed on the shallow side, there was insignificant small changes in heart rate.
- When they were placed over the deep side, however, their heart rates slowed significantly.

Development of Depth Perception

- The fact that heart rate decreased rather than increased suggests that the infants were not afraid on the deep side but were studiously attending to the depth information.
- Consistent with this interpretation, they cried and fussed less on the deep side than on the shallow side.
- It therefore appears that children as young as two months old are already able to perceive depth but have not yet learned to be afraid in the cliff situation.

Stereoscopic and Dynamic Information

- Once infants are able to converge their eyes, they can develop stereoscopic vision.
- Several different procedures indicate that depth perception based on binocular disparity develops at about 3.5 months of age, slightly after direct methods indicate that the ability to converge properly develops.

Stereoscopic and Dynamic Information

- Perhaps the best candidate for inborn dynamic depth information is looming (the motion gradient of an approaching surface) because it applies to objects coming toward a stationary observer.
- Newborns cannot really move themselves enough to produce extensive self-generated optic flow, but biologically significant objects—such as Mom and their own limbs— do move toward and away from babies as soon as they are born.

Stereoscopic and Dynamic Information

- Human babies one to two months old respond to looming (that is, visually expanding) objects with appropriate defensive reactions.
- They push back with their heads and lift their arms in front of their faces when contours expand in their field of view.
- These researchers interpreted such findings as indicating that depth information from a looming object is present very early in life, perhaps even at birth.

END OF PART 2

- Ref: Handout