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Figure-Ground Separation

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FIGURE-GROUND SEPARATION

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FIGURE-GROUND SEPARATION

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RUNNING HEAD: Figure-Ground Separation

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1. INTRODUCTION:

When we observe the world through one or both of our eyes, we readily perceive objects that are distinct from one another and from their scenic background. This competence is often called figure-ground separation. Figure-ground percepts are so ubiquitous and immediate that their remarkable and paradoxical nature is often not evident to a naive observer. When we reflect, however, that the three-dimensional (3-D) world is projected onto the two-dimensional (2-D) surface of each eye's retina, then figure-ground separation seems harder to understand. When we consider, further, that object or figures often seem to pop-out from their backgrounds even when we view a 2-D picture with a single eye, then the process may seem mysterious indeed.

Many factors can contribute to figure-ground separation, including differences in luminance, color, size, binocular disparity, and motion between a figure and its background. An analysis of all these factors would require a comprehensive study of visual perception. The present chapter has a more limited goal. It summarizes perceptual data that clarify key issues which must be dealt with to understand figure-ground perception, including data about how luminance contrast, binocular disparity, and spatial scale contribute to figure-ground separation in response to both 3-D scenes and 2-D pictures. An outline is then provided of how these data may be explained by a recent model of how the visual cortex works. Although unfamiliar objects can be separated from unfamiliar backgrounds, prior knowledge about the world can also facilitate figure-ground separation. A framework for analysing how unfamiliar figures may be separated, yet how knowledge may modulate or facilitate the separation process, will also be summarized.

2. SIZE DIFFERENCES DUE TO PERSPECTIVE:

It has been known since the Renaissance that the perspective with which a 2-D drawing or painting is rendered can make a figure appear to pop-out from its background. Typically, a large foreground figure (say of a person) in front of small background figures (say of trees,

houses, and hills) makes the foreground figure appear nearby and the background figures appear farther away. A 2-D picture can thereby generate a 3-D percept. This type of observation is consistent with the maxim that “large size scales signal near objects.”

As with many other properties of visual perception, this maxim is not always true, as will be noted below. Whatever its cause, 3-D percepts derived from 2-D perspectives show that the points and lines of Euclidian geometry and the surface elements and normals of Gaussian geometry are insufficient to explain figure-ground separation. New geometrical ideas are needed to explain how a 2-D picture can generate a 3-D percept. In this new geometry, points and lines are generalized to emergent boundary segmentations, and surface elements and normals are replaced by the filling-in of surface properties. What these segmentation and surface processes are and how they work is indicated below.

3. BINOCULAR DISPARITY AND THE SIZE – DISPARITY

CORRELATION:

Image size alone is not a completely reliable cue to a figure’s depth with respect to its background. In particular, a nearby small object and a far away large object may both subtend the same “size” on the retina. Another cue to depth is the different relative positions, or binocular disparity, with which an object is registered on an observer’s two retinas. Under a variety of viewing conditions, nearer objects generate a larger binocular disparity than farther objects. For example, objects viewed from a great distance generate an approximately zero disparity on the retinas.

By combining information about size and disparity, much more can be inferred about a figure’s location relative to its background. For example, two objects may generate identical retinal image sizes, but the one that generates a larger disparity under appropriate viewing conditions will be closer, and therefore smaller. This linkage between size and disparity is often called the size-disparity correlation (Julesz and Schumner, 1981). It has often been proposed that larger receptive fields, or spatial scales, preferentially represent the size-disparity

correlations of nearer, and thus larger and binocularly more disparate, objects. Although such an implementation of size-disparity correlation may abet figure-ground separation, it is not sufficient, as the next examples show.

4. DAVINCI STEREOPSIS:

Many figure-ground percepts can be better understood by analysing the following type of ubiquitous experience. When we view a farther surface that is partly occluded by a nearer surface, one eye typically registers more of the farther surface than the other eye does. Our conscious percept of the farther surface is often derived from the view of the eye that registers more of this surface. For example, under the viewing conditions depicted in Figure 1, observers see surface BC at the same depth as surface CD, even though surface BC is registered by only the right eye. Thus BC is part of the same “figure” as CD, even though only CD benefits from binocular disparity cues. This perceptual situation is often called DaVinci stereopsis (Nakayama and Shimojo, 1990). The challenging perceptual properties that subserve this percept will now be illustrated under simpler stimulus conditions.

5. DEFORMABLE FUSION BY ALLELOTROPIA:

Because each eye views the world from a different position in the head, the same material point on an object is registered at a different location on the two retinas, except for that object region which is foveally fixated by both eyes. To binocularly fuse such a disparate pair of monocular images, the two images must be deformed into one percept, as in the phenomenon of *displacement*, or *allelotropia*. Here, when a pattern EF G is viewed through one eye and a pattern E FG is viewed through the other eye, the letter F can be seen in depth at a position halfway between E and G. Thus the process of binocular fusion deforms the two monocular appearances of F into one binocular percept of F whose spatial position differs from either monocular position of F with respect to E and G. This deformation of F’s relative position is necessitated by the disparity of the two monocular F positions when E and G are binocularly fused.

During inspection of a 3-D scene, the amount of deformation needed to achieve binocular fusion depends upon how far away each object is with respect to an observer's retinas, since images of closer objects are more disparate than images of further objects. Thus different parts of the left eye and right eye images are deformed by different amounts to generate a single binocular percept of the world. During DaVinci stereopsis, the vertical boundaries of regions AB and CD in the left eye and right eye images of Figure 1 need to be deformed by different amounts in order to be binocularly fused. If deformation of monocular boundaries occurs to form fused binocular boundaries, why are no "holes" created in binocular perceptual space?

6. DISTANCE OF ZERO – DISPARITY POINTS:

In particular, the retinal images of objects at optical infinity have zero disparity on the two retinas, and the disparities on the two retinas of corresponding object points tend to increase as an object approaches the observer. This is the familiar reason for assuming that larger size scales and disparities signal near objects. On the other hand, when both eyes focus on a single point on a planar surface viewed in depth, the fixation point is a point of zero disparity. Points of the surface that are registered by the retinas further from the fixation point generate larger binocular disparities. Why do planar percepts not recede towards optical infinity at the fixation point and curve towards the observer at the periphery of the visual field? Why does the plane not become distorted in a new way every time our eyes fixate on a different point on its surface? For present purposes, a key fact is that a "zero disparity" condition also occurs under monocular viewing conditions, as in detecting region BC of Figure 1. How does the monocularly viewed region BC inherit the depth of the binocularly viewed region CD?

Both the absence of "holes" in space due to boundary fusion and the inheritance by BC of the depth CD may be explained by a filling-in process that selectively completes a BC surface representation at a depth corresponding to that of region CD. In other words, the process

that fills-in the surface depth of CD in response to its binocular boundaries keeps flowing until it also fills-in BC. Demonstrations that a filling-in process completes depthful surface properties include those of Nakayama, Shimojo, and Ramachandran (1990) and Watanabe and Cavanagh (1992).

7. BINOCULAR AND MONOCULAR BOUNDARY SEGMENTATIONS:

The surface filling-in process is activated and contained by boundary segmentations. Some boundaries are derived from binocularly viewed parts of a scene, others from monocularly viewed parts. In Figure 1, binocular fusion of the AB boundaries and the CD boundaries registers different disparities and amounts of allelotropia. The monocularly viewed boundaries in region BC do not register any binocular disparity. Nor do the horizontal image boundaries. Thus at least three ways exist for an image to be registered with zero, or near-zero, disparity: as an occluded region during DaVinci stereopsis, as a monocularly viewed image, or as a horizontal boundary during either monocular or binocular viewing. Monocular and near-zero disparity cells are known to be separately processed by visual cortex (Poggio and Talbot, 1981). Grossberg (1994) suggested that monocular and near-zero disparity boundaries are processed in a separate pool of cortical cells for the following reasons.

8. MONOCULAR AND NEAR – ZERO DISPARITY CELL POOLS :

We need to explain how the monocularly viewed vertical and horizontal boundaries in region BC are joined with the binocularly fused, large disparity vertical boundaries and horizontal near-zero disparity boundaries in region CD to form the window frame in Figure 1. Disparity-sensitive cortical cells are tuned to a limited range of disparities. Let us assume that active near-zero disparity cells, whether they are monocularly or binocularly activated, give rise to spatially organized boundary signals that are combined with the spatially organized activations of cells that code non-zero disparities to create a more complete boundary representation (Figure 2a). The non-zero disparity cells are themselves assumed to be segregated into separate cell pools that are organized to correspond to different rela-

tive depths of an observed image feature. Thus near-zero disparity cells add their boundary activations to multiple boundary representations, each corresponding to a differently tuned pool of non-zero disparity cells.

In response to the scene in Figure 1, consider BC boundaries added to CD boundaries at those scales and disparities that are capable of computing binocularly fused CD boundaries. These composite BCD boundaries enclose *connected* regions, such as the connected window frame in the right eye image of Figure 1, if the following problem can be solved.

9. 3 – D EMERGENT BOUNDARY COMPLETION:

Due to allelotropia, the binocularly fused boundaries within region CD may be positionally displaced relative to the monocularly viewed boundaries within region BC. As a result, gaps may occur between the locations of cells in the visual cortex that represent binocular and monocular boundaries. When regions contain oblique contours, the binocular and monocular responses of cortical cells may be both orientationally and positionally displaced. These gaps and misalignments need to be corrected by a boundary completion process (Grossberg and Mingolla, 1985; see Leshner and Mingolla, this volume). Boundary completion is capable of generating an emergent boundary segmentation which realigns and connects the boundaries that join regions BC and CD. These completed boundaries completely enclose the window frame in Figure 1.

10. CAPTURE OF FILLED – IN SURFACE PROPERTIES BY CONNECTED BOUNDARIES :

The connected boundaries within region BCD form a sparse and discontinuous representation of the scene. How are the scene's continuous surface properties generated, to form a scenic figure, including its brightnesses, colors, and surface depths? Suppose that boundaries which enclose *connected* regions in BCD, and *only* these boundaries, can trigger filling-in of surface properties of the regions that form part of the final visible 3-D percept (Figure 2a). For this to work, multiple filling-in domains, or FIDOs, exist such that filling-in within each

FIDO is controlled by boundaries that are sensitive to a restricted range of binocular disparities (Figure 2b). An FCS input is broadcast to all the FIDOs that code its color. Filling-in is triggered in only those FIDOs where color signals (called FCS signals) and boundary signals (called BCS signals; see Section 14) spatially coincide (Grossberg, 1987, 1994). These boundaries “capture” the surface color for their FIDO. Filling-in is modelled as a diffusion of featural activity across a FIDO until it hits a boundary barrier (Grossberg and Todorović, 1988). The activity dissipates unless a connected boundary can contain it. As explained below, region BCD in Figure 1 contains a connected boundary within the FIDO, or subset of FIDOs, corresponding to the binocularly fused boundaries of region CD. Such surface representations combine position, depth, orientation, brightness, and color properties.

11. NEAR BOUNDARIES OBSTRUCT FILLING – IN OF OCCLUDED REGIONS:

How does the filling-in of surface BC at the depth of CD stop at boundary B? Boundary B is binocularly fused at a disparity corresponding to a nearer surface than are the boundaries of region CD. Without further processing, boundary B could not form a connected boundary around region BD. Nor could it prevent filling-in of region AB within the FIDO whose depth corresponds to region CD. Filling-in would also occur within the FIDO whose depth corresponds to boundaries A and B of region AB. If both filling-in events could occur, region AB would appear transparent: it would be represented by two different filled-in surface representations at two different depths from the observer. In fact, if filling-in is the basis for many depthful figure-ground percepts, then why do not *all* figures look transparent?

This will not happen if the boundaries of closer objects are added to the boundaries of further objects in the FIDOs (Figure 2b), so that near and far data are processed asymmetrically. Then filling-in initiated in region BD does not flow behind region AB. This restriction upon surface filling-in does not prevent *boundaries* from being completed behind an occluding region. Then pathways from boundary representations to the object recognition system

(Figure 3) enable partially occluded figures to be recognized via their completed boundaries, even if visible surface properties are not filled-in behind the occluding object.

These properties of DaVinci stereopsis illustrate how the multiple spatial scales that are used for disparity-selective early visual filtering may interact with later boundary segmentation and surface filling-in processes to bind visual features into surface representations of figure and ground.

12. LARGE SIZE SCALES SIGNAL FAR OBJECTS (THE WEISSTEIN EFFECT):

The Weisstein effect clarifies how depthful figure-ground percepts can occur in response to pictures that are constructed from multiple spatial scales or spatial frequencies. As noted above, large size scales, or low spatial frequencies, often seem to selectively process near objects, whereas high spatial frequencies selectively process far objects. In contrast to this property, Klymenko and Weisstein (1986) demonstrated that if regions filled with relatively higher spatial frequency sinusoidal gratings are adjacent to regions containing relatively lower spatial frequency gratings, then the regions with the higher frequency appear closer in depth than those containing the lower frequency. They studied a variant of the classical Rubens faces/vase reversible figure for which, in the absence of the sinusoidal gratings, a temporally bistable percept is perceived. At one instant, two faces pop-out as figures. At the next instant, a vase pops-out between the faces as they recede into the background. With a higher spatial frequency sinusoid placed within the faces than the vase, the faces are perceived as figures most of the time. The Weisstein effect shows that whether a spatial frequency difference signals “near” or “far” depends upon how the image is segmented into boundaries and surfaces, not merely upon a size difference *per se*.

13. 3 – D PERCEPTS OF OCCLUDED AND OCCLUDING FIGURES IN 2 – D PICTURES:

The spatial organization and relative luminance of occluding and occluded objects also

has a powerful influence on figure-ground perception during inspection of 2-D pictures as well as 3-D scenes (Bregman, 1981; Kanizsa, 1979). Comparing Figures 4a and 4b shows that the occluding black sinewy shape in front of the occluded B's is needed to readily recognize them as B's.

How does a 2-D image create a 3-D percept of occluding figures in front of occluded figures, as in Figure 4a? How are the gray fragments easily recognized in Figure 4a as occluded B shapes but not in Figure 4b, even though they are equally well seen in both? A comparison of Figures 4a and 4b illustrates that properties of contrast, form, and depth interact to generate a percept, and that this interaction may, as in Figure 4a, generate a 3-D representation of a 2-D image. This 3-D representation enables the occluded boundaries of the B shapes to be completed for purposes of recognition, even though the occluded surfaces are not seen in either figure. How does this happen?

Suppose that the boundaries which are shared by the gray B shapes and the black occluder are assigned to the occluder and detached from the remaining B boundaries. Suppose also that these shared boundaries, along with the other occluder boundaries, are used to generate a boundary segmentation and filled-in surface representation of the black occluder "in front of" the surface on which the B fragments lie. These boundaries are also reattached to the B boundaries at a later processing stage, as in DaVinci stereopsis, to keep the gray from flowing behind the black.

14. OCCLUDED BOUNDARY COMPLETION AND RECOGNITION WITHOUT FILLING – IN:

Given that the shared boundaries between occluder and B shapes in Figure 4b are somehow removed from the B shapes, how does an observer so quickly recognize the incomplete B figures? As in the case of DaVinci stereopsis, a boundary completion process generates illusory contours between the (approximately) colinear line ends of the incomplete B figures. This property of illusory contour completion raises a central question in figure-ground per-

ception: if illusory contours complete the B shapes and thereby enhance their *recognition*, why do we not *see* these illusory boundaries in the sense of detecting a perceived brightness or color contrast at their locations?

Figure 3 schematizes part of the answer that was proposed by Grossberg and Mingolla; see Lesher and Mingolla (this volume). A boundary that is completed within the segmentation system (which is called the Boundary Contour System, or BCS) does not generate visible contrasts within the BCS. In this sense, *all boundaries are invisible*. Visibility is a property of the surface filling-in system (the Feature Contour System, or FCS). The completed BCS boundary can directly activate the visual Object Recognition System (ORS) whether or not it is visible within the FCS. Neurophysiological data suggest that the ORS includes the inferotemporal cortex (Mishkin and Appenzeller, 1987), whereas the FCS visible surface representation includes area V4 of the extrastriate cortex (Desimone, Schein, Moran, and Ungerleider, 1985; Zeki, 1983). A boundary may thus be completed within the BCS, and thereby improve pattern recognition by the ORS, without necessarily generating a visible brightness or color difference within the FCS. In the classical literature, such boundaries were said to be *amodally* completed, but the relationship between amodal completion, modal completion, and filling-in was not specified.

15. 3 – D KANIZSA SQUARES:

3-D Kanizsa squares provide a vivid example of how boundary and surface processes interact to define figure and ground occurs. When one inspects a 2-D Kanizsa square (see Lesher and Mingolla, this volume), one perceives a square boundary that encloses a bright square region. A square illusory contour is generated by four black pac-man figures and triggers selective filling-in of the bright square region.

3-D Kanizsa square percepts illustrate how binocularly fused boundaries can generate illusory boundaries that selectively capture the brightness signals induced by the pac-man figures to fill-in two surfaces at different perceived depths from the observer. In Nakayama,

Shimojo, and Ramachandran (1990), the disparity of the vertical boundaries in the pac-man figures of two Kanizsa square images was varied. The image pairs were viewed through a stereoscope or free fused. In the crossed disparity case, which corresponds to closer objects, the illusory contours that frame the square are greatly enhanced and the Kanizsa square appears nearer. Observers recognize that the pac-man boundaries are completed into disks behind the square surface, but only the pac-men are seen as visible surfaces. When the disparity is reversed, an occluding surface is perceived through whose four (almost) circular windows are seen the four corners of an occluded square. The illusory contours that complete the four circular windows are visible because the occluding surface fills-in at the nearer depth. The Kanizsa square is recognized behind the occluding surface, but only its four pac-man regions are visible through the four circular windows.

These remarkable percepts show that binocular matching of just a few edges in a scene can trigger completion of a 3-D boundary segmentation that captures figural surface percepts at the relative depths that the boundaries encode. Also, once again, the ORS may *recognize* the BCS boundaries that are completed behind the nearer occluding surface, even if they are not *seen* within the FCS. They are not seen within the FCS whenever the BCS boundaries of nearer segmentations create barriers to filling-in of farther surfaces, as in Figure 2b. These and many other figure-ground percepts can be explained by such model rules (Grossberg, 1994). Leshner and Mingolla (this volume) introduce some of the monocular properties of the BCS, including the simple, complex, hypercomplex, and bipole cells of the visual cortex that the BCS models.

16. CONCLUDING REMARKS:

The above experimental data and theoretical concepts suggest that figure-ground separation in particular, and biological vision in general, uses principles and mechanisms that are very different from those described in classical geometries and computer vision algorithms. These new ideas are naturally expressed using suitably defined neural networks in which the

complementary properties of emergent boundary segmentations and filled-in surface representations are interactively combined.

17. ACKNOWLEDGEMENTS:

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FIGURE CAPTIONS

Figure 1. A DaVinci stereopsis display. [Figure reprinted with permission from Grossberg, 1994.]

Figure 2. (a) Near-zero disparity and monocular boundaries are added to boundaries of all the selective pools of non-zero disparity cells (with disparities D_1 and D_2). Only regions enclosed by connected boundaries can fill-in. Other regions dissipate activity through uncontrolled diffusion. (b) Multiple FCS copies exist corresponding to the BCS copies that code different ranges of relative depth from an observer. Each FCS copy contains a complete set of Filling-In Domains, or FIDOs that correspond to the opponent colors (red, green), (blue, yellow), and (black, white). Near boundaries add to far boundaries in the FCS copies to prevent filling-in from occurring behind opaque surfaces. [Figure reprinted with permission from Grossberg, 1994.]

Figure 3. Completed boundaries within the Boundary Contour System (BCS) can be recognized within the Object Recognition System (ORS) via direct BCS — ORS interactions whether or not they are seen in the Feature Contour System (FCS) by separating two regions with different filled-in brightnesses or colors. [Figure reprinted with permission from Grossberg, 1994.]

Figure 4. Role of occluding region in recognition of occluded letters: (a) Upper case “B” letters partially hidden by a black snake-like occluder; (b) same, except occluder is white, and therefore merges with the remainder of the white background. Although the exposed portions of the letters are identical in (a) and (b), they are much better recognized in (a). [Reprinted with permission from Nakayama, K. Shimojo, S., and Silverman, G.H., 1989, Stereoscopic depth: Its relation to image segmentation, grouping, and the recognition of occluded objects. *Perception*, **18**, 55–68.]

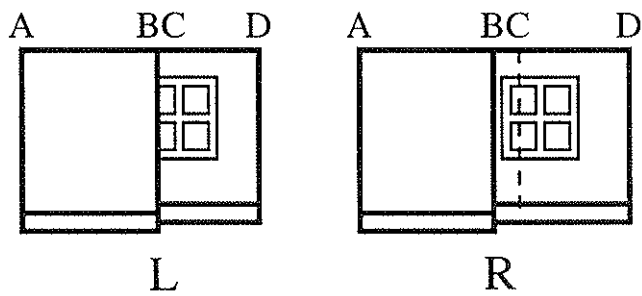


Figure 1
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Figure-Ground Separation

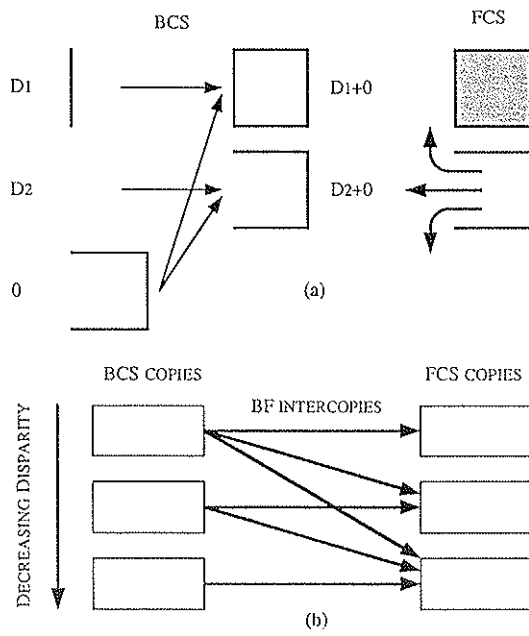


Figure 2
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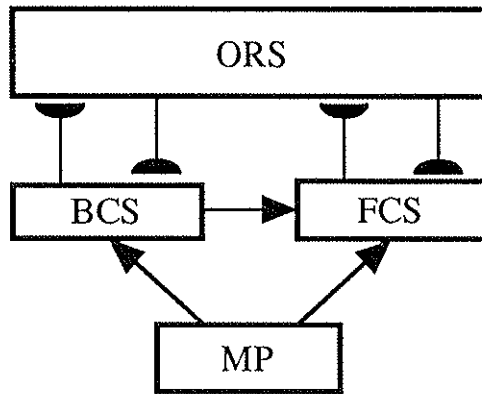


Figure 3
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Figure-Ground Separation

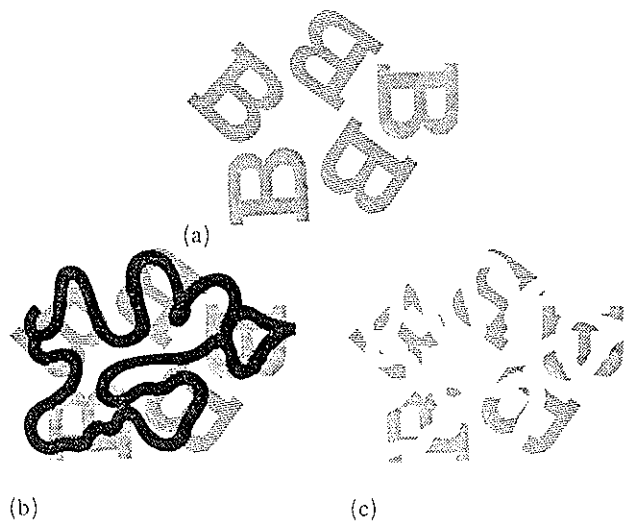


Figure 4
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