The Art and Science of Depiction

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Abstract

This text deals with the depiction of reality on a 2D medium, or more simply “pictures”. This study gathers elements from computer graphics, art history and experimental psychology. We will first show the limits of the notion of a perfect and passive record of reality. We then define the elements that come into play in the chain of the production/observation of a picture (reality, artist, technique, 2D medium, observer). We briefly present the human visual system, crucial element in understanding pictures. We then describe the underlying limitations of the medium, and the possible compensation techniques. Finally, we give a taxonomy of the technical elements involved to create a picture.

Figure 1: René Magritte *La condition humaine*, 1933.

Figure 2: From [SCCZ00].

1 Introduction : The quest for Realism

This article presents no new technique, just an attempt to step back from computer graphics and place it in the broader context of pictures and visual arts. We hope that it will permit the exploration of its mechanisms, constraints and wealth.

Realism has traditionally been one of the great challenges of computer graphics. It is mainly in rendering that this quest for “truth” has been paramount, with simulations relying on the physics of light transport, the interaction between light and material and the mathematical theories of integration and finite elements. Today, the goal seems close, as shown by the astonishing special effects exhibited by block-buster films.

Art history has also long been thought of as a very scientific search for realism, especially from the Renaissance to the 19th century. Artists such as Leonardo, Dürer or Constable have left evidence of their systematic approach towards an ever more faithful representation, and art historians have long described the evolution of style as a journey towards perfect realism. Ancient styles were then considered as a consequence of the clumsiness of their authors.

The advent of photography may have seemed to close the issue. It is of particular interest for us, since it is usually used as a reference of realism, as shown by the term “photorealism”. However, if it has deeply changed the world of pictures and artistic practice, photography remains an art that requires skills to obtain the best results. The photos that we take are often disappointing and fail to reproduce scenes that looked so beautiful to us. When Talbot, one of the inventors of photography, called it “the pencil of nature”, he meant to emphasize the perfection of the recording. We will see that the metaphor can be extended to the limitations of painting as well.

This article starts from a discussion about realism. Is it possible to reach perfect realism? Is it desirable? Why and how can a picture evoke a reality? Does the notion of “non-photorealistic rendering” [LS95, Rey00, Gre99] have a meaning? Is it useful?

More generally, our goal is to introduce the mechanisms involved in the reproduction of reality on a two-dimensional medium: canvas, photo, print, monitor, etc. We believe that computer graphics has a lot to learn from the know-how that artists have gathered through centuries and from the understanding now offered by experimental psychology. We will focus on introducing the issues rather than providing solutions. We will deal mainly with static images (and thus mainly about rendering in computer graphics), but we will try to broaden our subject by references to animated images when relevant.

We will deal much with artistic pictures, mainly because of the vast amount of dedicated studies, but also because it is one of the oldest activities of mankind [Gom95b]. We will not raise the philosophical issues of "$\mathcal{B}$eauty" or "$\mathcal{A}$rt" that are way beyond the scope of this text. We however do not claim that artistic images can be understood by only studying them as depiction of a reality. Moreover, we will not confine this article to aesthetic images, but we will try to encompass pictorial depiction in general, be it functional, documentary or aesthetic.

We will introduce the limits of the notion of passive and perfect recording, with examples from photography and cinema. We will try to understand what an image is in general and how it is created and observed. We will see that understanding the human visual system is crucial. We will show the limitations of the medium, their consequences in terms of realism of the images and the possible compensations. Finally, we will draw a classification of the systems of pictorial technique.

2 Film: a reality capturing device?

To reach the Holy Grail of photorealism, computer graphics has attempted to simulate reality more and more accurately. However, when closely studying the techniques used by photography and cinema artists, one realizes that they often have to bypass and modify the conditions that reality spontaneously offers.

2.1 Photography: artifacts more realistic than reality?

Photo-graphy means "writing with light". Photorealism has thus been sought by reproducing with high fidelity the physics of light transport and interaction between light and materials. Nonetheless, one of the keys of the art of photography is mastering light [Low99]. The photographer is never passive towards light, both when he uses available light or when he installs his own. For exterior shots, sunset and sunrise are sought for their lighting quality. For a portrait with natural light, a small flash is often welcome to "fill-in" too sharp shadows, and many photographers use artificial projectors and reflectors to improve natural lighting. Studio photography is characterized by its complex installation of light source [Low99, Mil91](Fig. 3). This is far from a passive use of available light. A high quality lighting must be worked on. Realism often requires the addition of artificial light sources.

Human-beings remain one of the major challenges of computer graphics. The BRDF (reflectance function) of skin is very complex; it varies according to the presence of veins, the thickness of its various layers, the tension and the layer of fat that covers it. We are moreover very critical; our sensitivity is very acute when it comes to looking at humans. But one must wonder how useful it is to model human skin with high precision when the first step for a portrait is the addition of a thick layer of make-up (Fig. 4). The skin with its artificial make-up looks more real, or at least more satisfying than real skin.

The prints coming out of automatic processing machines (minilabs) are often very disappointing, especially for black and white photos. Printing is an art. If a photographer does not do it by himself, he usually remains faithful to the same printing professional, because his importance is so high. By playing with chemical components, papers and processing time, the printing artist can control the tone reproduction curve [SCCZ00, Hun95, Ada95]. For example, the *Zone System* is a technique consisting of controlling the mapping between intensity levels of the negative (zones) and the print. *Masking* uses cardboard masks to hide parts of the images to

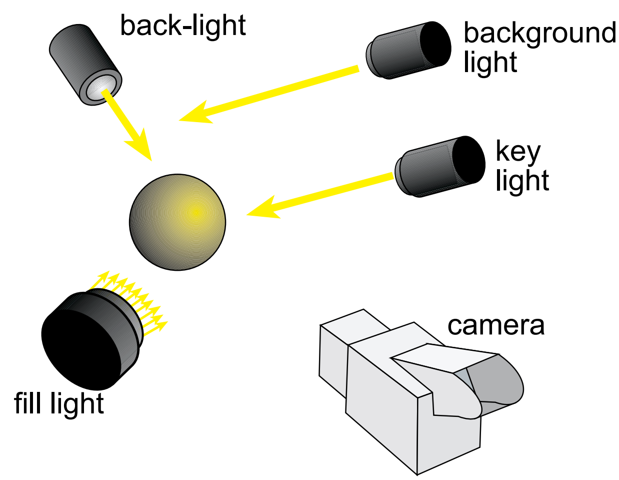


Figure 3: Three point lighting (adapted from [Mil91]). The *fill* lamp permits to fill-in shadows. The back light emphasizes the silhouettes of the subject. The background often has a different lighting.

Figure 4: Make-up session and final photo.

make them lighter. A photo is not even a passive and direct reproduction of the negative.

Black and white photography cannot claim to reproduce reality since our world is colorful. However, the reproduction of color is a complex science, far away from a simple colorimetric recording [Hun95]. We know that some colors are impossible to reproduce with most classical synthesis systems, in particular blue-green. Other complex effects occur. We usually prefer tanned skin, blue sky and very green grass. When looking at a photo, we compare what we see to these idealized colors rather than to the actual colorimetry of real objects. Similarly, the nineteenth century painter John Constable argued that the color of grass that people expect in paintings is not faithful to reality [Gom56].

A photo is only a snapshot of reality. This corresponds to the choice of the "decisive moment" of Henri Cartier Bresson. The ability to freeze movements is pushed to its limits in Harold Edgerton's ultra-fast photography [Edg87], that reveals us surrealist scenes, though completely real (Fig. 5(a)).

The photographer has not only the choice of the viewpoint, but also the choice of perspective, Wide angle photos exhibit a field of view and distortions that are very artificial. Satisfying architectural photos are obtained by using special tilting lenses (the optical axis is not orthogonal to the image plane) that allow parallel verticals and perfect rectangular facades on the photo. Nonetheless, when one looks at a facade from below, foreshortening actually makes the top appear with a smaller visual angle. Realism should thus impose converging verticals.

(a) (b)

Figure 5: (a) Bullet through a card (photo H. Edgerton). (b) Simple special effect (photo Scott Johnson).

The most simple of special effects simply consists in visually putting a far away character down on the hand of a foreground character, who then looks like she's talking to a Lilliputian subject (Fig. 5(b)). Photography represents spatially distant objects on a same plane. This is of course also related to to depth of field, which can be chosen from very narrow to infinite. This choice can be linked to the capacity of our eye to focus on different objects, but at a given time, it can never be focused on the whole scene.

2.2 Cinema : space-time turned upside-down

Realism in cinema and on television presents the same paradox discussed above, but the temporal dimension enriches them and adds new discrepencies.

Our cinema is organized around the notion of shot or sequence [Arn57, Ari91]. Although our Newtonian conception of time is linear and continuous, the camera viewpoint changes discontinuously, time is compressed or omitted, or even worse, flashbacks reverse the course of time. A good editing is the opposite of a passive retranscription of time. It must have a very good rhythm to keep the attention, interest and immersion of the spectator. Even live recorded broadcast play with time through replays and slow motion.

As for studio photography, cinema or television lighting is much different from normal lighting conditions. All direct spectators report their surprise when they see the flatness and uniform impression conveyed by the lighting. Moreover, to appear unchanged on screen from one shot to the other, lighting often has to be changed [Mil91]. The same lighting filmed from different viewpoints seems changed. It has to be modified to look unchanged.

Other examples of discrepancies can be found in the placement of actors. For example, during close-up dialogs, actors are usually placed closer than they would normally for nicer composition [Ari91]). Some motions have to be adapted to be more "visual". Martial art films are a good example. Bruce Lee has had to modify his style, because side kicks look better on screen. Similarly, the swimming champion of the 20's, Johnny Weissmuller, one of the best swimmer ever, had to re-learn how to swim for the *Tarzan* movie, because his very efficient style did not show the impression of manly effort expected from the ape man! Moreover, we all know intellectually that most of the stunts and special effects are not only "rigged", but they are strictly physically impossible. It is the magic of cinema that makes them believable.

Apodaca [AG99] also describes all the "tricks" used in computer graphics imagery to adapt realism to the needs of story telling. Blinn called it the ancient art of *Chi-Ting* [Bli84].

2.3 What about paintings?

La source by Ingres (Fig. 6) exhibits a natural and graceful young woman. The impression of ease and serenity is reinforced by the balance of the painting. However, if one looks more closely, the pose of the model is very unnatural and must be very uncomfortable [Arn54]. Nevertheless, projected on the canvas, the pose looks simple and natural. The same is true for many photographic portraits.

Figure 6: Jean-Auguste-Dominique Ingres, *La Source*, 1856.

There are even cases where painting reveals superior capability to photography. Most of the indoor scenes depicted with such a realism by the Dutch Masters of the 17th century are nightmares for photography, in terms of both perspective (lack of distance) and lighting (too high contrast, too low light level) [Pir70].

2.4 Can a recording be passive and perfect?

We could first conclude that there are scenes or reality that are photo-friendly, for which the film would record a faithful image. Some people are said to be "*photogenic*", we know that certain lighting conditions are favorable, etc.

However, we have also shown that some very realistic-looking images are actually the recording of an "artificial" configuration. Fundamentally, any photograph is an active recording: the photographer chooses the point of view, focal length, instant, lighting, etc.

We are so used to using photography as a standard for realism, that we forget that a photo almost never produces the complete illusion of reality: we clearly see that it is a flat image that is absolutely not real. However, a photo has this kind of magic that allows us to recognize a reality. We will come back to this dual nature, both 2D object and representation of a 3D scene.

Trompe-l'œil [Mas75] is an extreme case of images that is possible only in specific conditions, in particular, limited depth of field. Even a masterpiece such as Pozzo's ceilings (Fig. 7) is not a complete illusion because of the luminosity difference between the painted and real sky visible through windows [Pir70].

Figure 7: Fra Andrea Pozzo,ceiling of the St Ignacio church in Rome, 1693-1700.

Recording can be pushed further, using stereo images, IMAX-like films, etc. One then gets closer and closer to the *mimesis*, but the viewpoint remains the *choice* of the artist, as are the subject and the instant. Maybe techniques such as animated light fields, force feedback will permit a quasi-perfect recording and immersion. However, when it comes to purely 2D images, any representation of reality is by nature partial and imperfect.

As underlined by Gombrich [Gom82], an image is a choice, a judgment that uses a process of selection and omission. The myth of the innocent eye is an illusion.

2.5 Relativity of réalism

The judgment of realism evolves with time and cultures [Arn54, Gom56]. For example, the contemporaries of Giotto said that there was nothing that he could not depict with perfect realism. But when we look at his paintings nowadays, they look far from the realism of photos. It is easier to understand when we compare it to the paintings of his time (Fig. 8). Transcending standards establishes the norm for realism.

Similarly, when Conan Doyle and O'Brien showed the first sequences of *The Lost World* in 1925, the audience was dumbfounded and thought that Conan Doyle had actually found dinosaurs in a lost plateau. Today, these stop-motion animation still look excellent, but the trick is obvious. Will our criticism of the special effect of Spielberg's version undergo the same evolution?

Figure 10: *The Lost World*. (a) The original by Conan Doyle and O'Brien (1925), stop-motion animation. (b) Spielberg's version with digital effects (1997).

3 What is an image?

After this brief review of the equivocal relations between realistic images and reality, it is time to define with more precision the phenomena involved in the creation and observation of images.

3.1 The chain of the representation of reality

Four main actors can be distinguished: reality (or scene), artist, image and observer (Fig. 11). The essential go-between is of course the pictorial technique or practice.

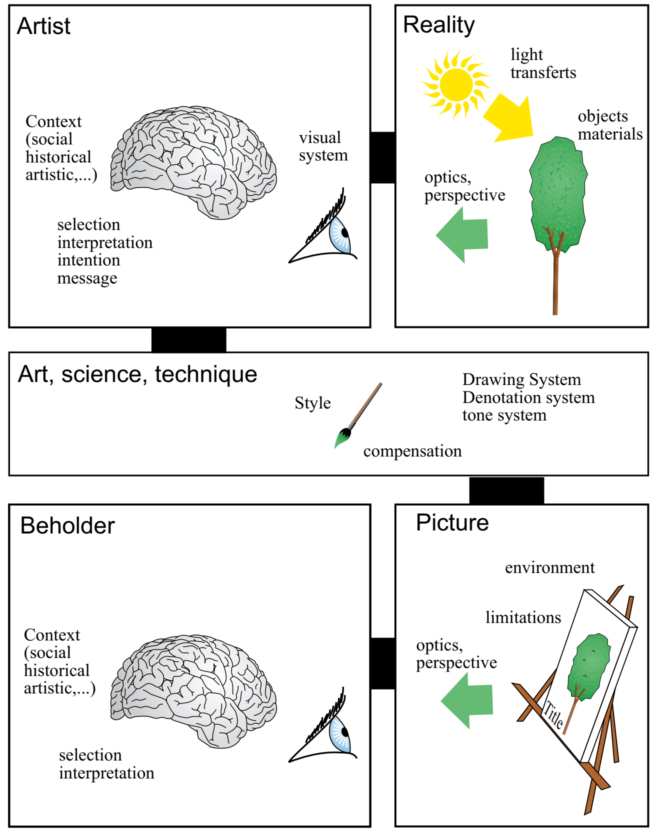


Figure 11: What an image is.

Reality is characterized by objects and complex optical or luminous phenomena. These issues are well understood (if not solved!). We will not really deal with these issues. However, modeling reality still raises great challenges, in terms of geometry, photometry, and materials [Fou99].

Note that reality is not always directly present as a model. However, the observation of reality is always used as a reference and basis for imagination. Similarly, it is interesting to note that most of what will be said about man made images will also be valid for our observation of the figures accidentally formed by natural objects such as clouds or star constellations.

The artist perceives reality through his visual system. This is far from a simple recording of light reaching the retina; human vision is a complex phenomenon that is still not completely understood. This issue will be treated in the next section. The retinal image is analyzed, recognized, cogitated, and its perception depends on the context, be it personal, sociological, historical, etc. the other senses can also play a role (everybody knows that it is more beautiful to take pictures of churches when the bells ring).

Behind an image, there is always an intention, a goal, a message.

The artist then retranscribes reality on a medium (canvas, paper, photo, display). The medium has its own physical and visual characteristics. They impose limitations that the artist may or may not want to compensate, as will be discussed in section 5. Moreover, an image is rarely alone, it is usually placed in an environment that affects its perception.

Finally, the observer sees the image through his visual system,

Figure 8: *The Madonna*. (a) Cimabue version (attributed Duccio), around 1275-1280. (b) Version of Giotto, 1310.

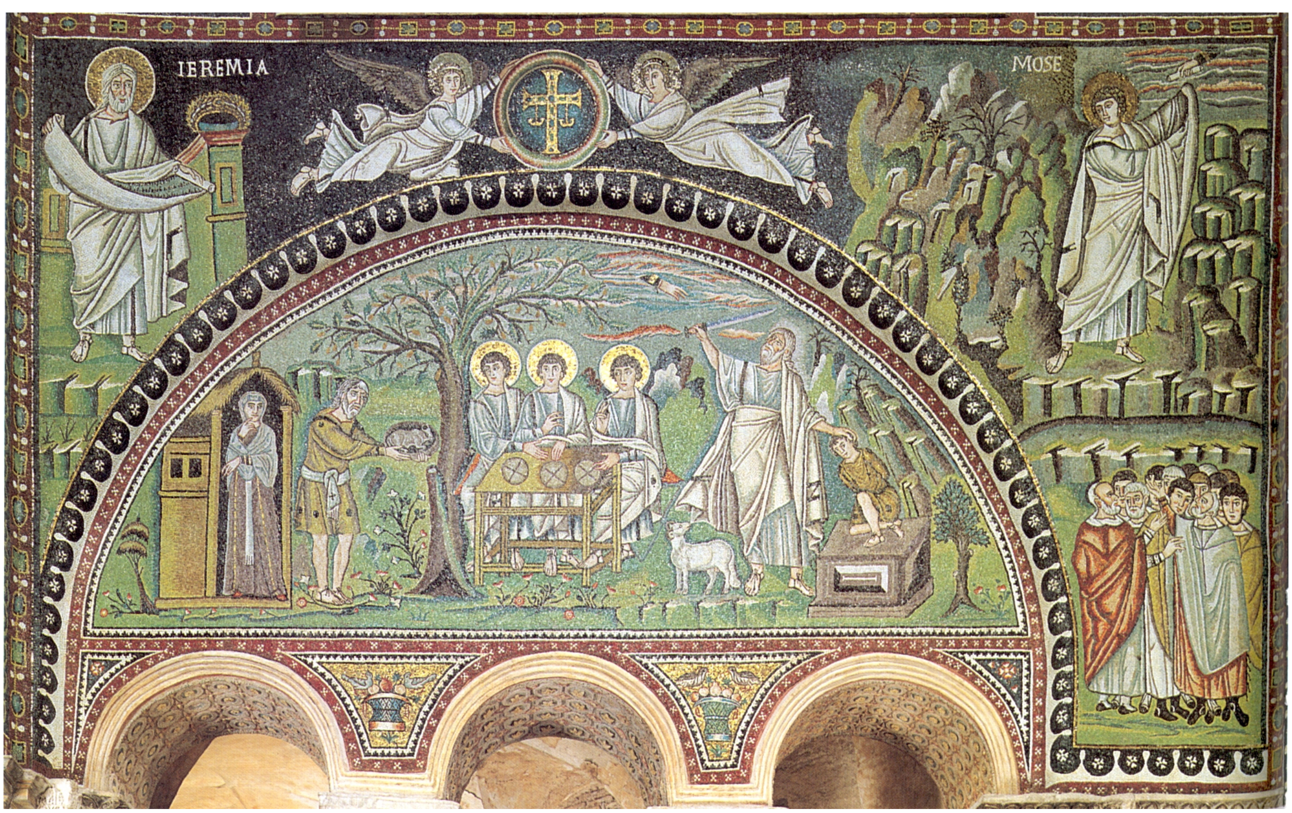


Figure 9: *Scene of the life of Abraham*, mosaic of the San Vitale basilica, in Ravenna, around 532. In this image, the 2D aspects are often prevail over 3D aspects: for example, the leftmost tree is bent to follow the limit of the image.

that is mostly similar to the artist's, but he often has a different personal or historical background. Different observers do not necessarily see the same things in a given painting. The lack of an appropriate context can lead to misinterpretations. Hence the importance of titles, as illustrated by *l'Almanach* by Desproges [Des89] where *Guernica* by Picasso takes on very different meanings on each page ! *Christina's world* by Wyeth (Fig. 12) is another example: the painting takes a completely different meaning when one understands that the young women is paraplegic and that this painting depicts her whole world. Hence the difficulties in understanding art from the past or some modern art for which we miss "keys". For this, *the Story of Art* by Gombrich is a wonderful introduction.

Figure 12: Andrew Wyeth, *Christina's world*.

The technique that allows the artist to retranscribe reality into a two dimensional picture will be discussed in section 6, where we will study the different technical choices involved. These choices are one of the facets of the unutterable notion of *style*.

3.2 Double nature of pictures

A picture has a double nature: it is both a flat object and the representation of a 3D reality. This duality raises conflicts between properties of the object image and properties of the objects in the image. These conflicts are the cause of many limitations, but also a source of richness.

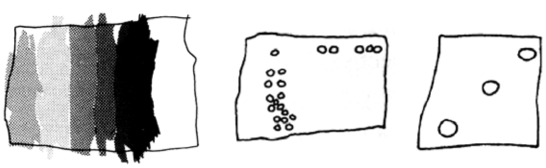


Figure 13: Drawing of a cube by children [Wil97]. The first cube had a different color for each face. It has been depicted as a rectangle, but this rectangle does not stand for the view of only one face, since all the colors are present. In fact, the notion of a 3D object with corners has been depicted as a 2D object with corners. Similarly, the second drawing represents a game dice. The unique square contains all the numbers. Only the rightmost drawing corresponds to a "valid" perspective view.

A feature of the image may be described with respect to the 2D nature of the image, or with respect to the depicted 3D reality. Take the example of a perspective view of a square. It can be described as a diamond-shape in 2D, or as a square in 3D, with different properties in the two cases, such as the presence or not of perpendicular corners. Here, is more than the simple notion of perspective projection, as shown by the experiments done by Willats (Fig. 13)[Wil97].

We will see in this text that the interaction and the competition between these two natures is the basis of many problems and wealth of pictures. A first possible approach is to choose the scene and projection such that 3D and 2D properties match, or to make sure that one aspect reinforces the second one, as is done with good lighting or photogenic people. Another approach is to inflame the discrepancy between image and object space.

Figure 14: Pablo Picasso, *Arlequin assis (Le peintre Jacinto Salvado)*, 1923. The coexistence of two styles (drawing and oil) underlines the duality between image and depicted reality.

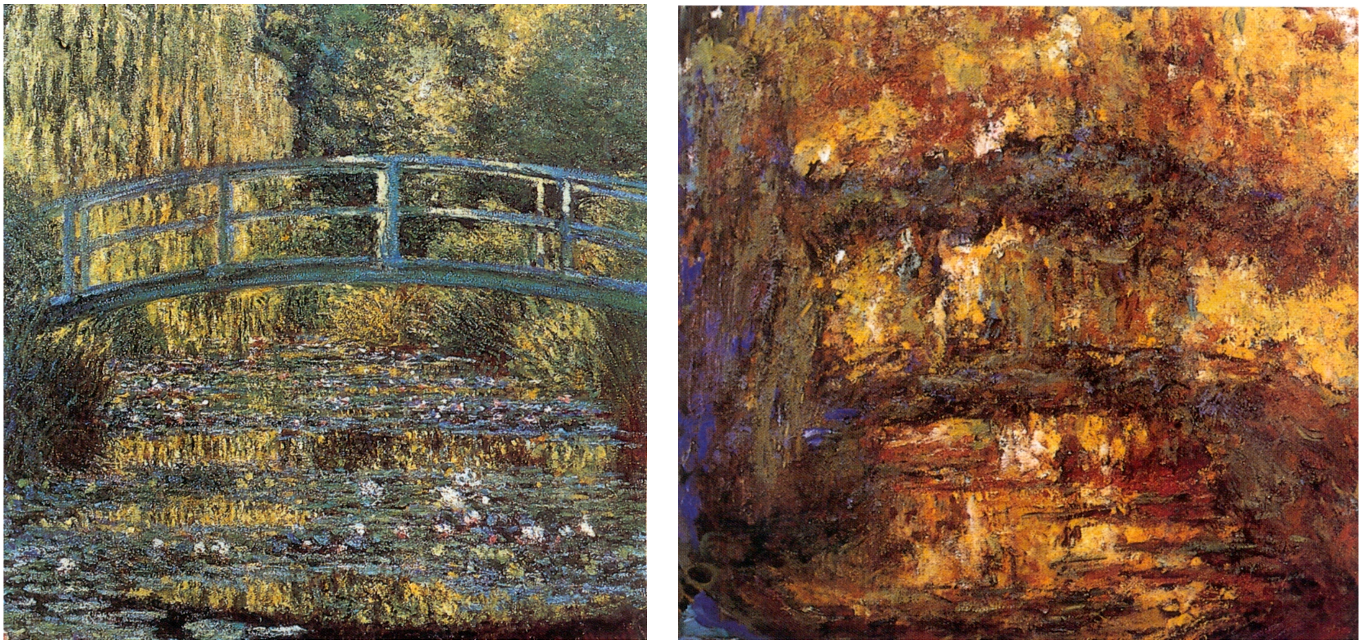
The duality of images is illustrated by the famous painting by Magritte *Ceci n'est pas une pipe*, or by the following anecdote [Gom56]. A lady, looking at one painting by Matisse, told him that the arm of one woman was too long. He replied that she was mistaken, that it was not a woman but a painting.

4 The human visual system

Human vision explains many phenomena from the world of images. Reciprocally, artistic techniques are hints about the way our vision works [Cav90]. More details on visual perception can be found in [Wan95, BGG96, Pal99, Fer98, CPS00].

4.1 A set of specialized analyzers

Even at the lowest level of our perception, in the retina, visual information is processed and analyzed, in particular by center/surround mechanisms. The wiring of the neurons following the receptors make them sensitive to contrast, in a way similar to edge detection in computer vision (Fig. 17 and 18). This mechanism explains the efficiency of line drawing (Fig. 19).



(a) (b)

Figure 16: Influence of Monet's cataract on his works. (a) *Le bassin aux nymphéas* painted in 1899, before his cataract, exhibits cold hues and a sharp image. (b) *Le pont japonais* painted in 1922, shows a strong yellowish dominant and fuzzy shapes. After [Lan00].

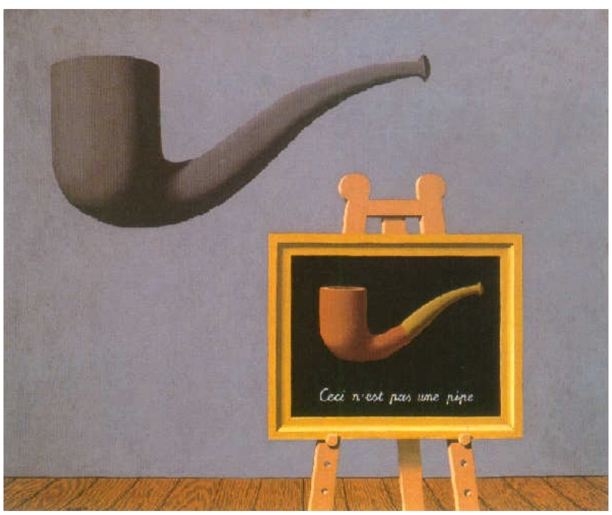


Figure 15: *Les deux mystères* (René Magritte).

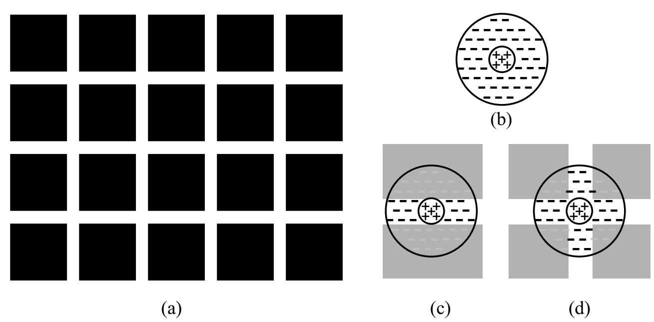


Figure 17: (a) Hermann grid: illusory dark spots appear at the intersections. Note that the effect is more efficient in semi-peripheral vision, because of the different retinal resolution. (b) Center surround organization or receptors. Each sign represents the input from a receptor. (c) Many negative input activated, strong signal. (d) Weaker signal (After [GG73]).

Similar mechanisms permit the treatment of colors, more global shapes, motion. The information is quickly separated into components representing color, temporal aspects, shape and higher level concepts. For example, a whole region of the visual cortex is dedicated to the recognition of faces.

The characteristics of each of these mechanisms can help understand how to stimulate them, in order to obtain pictorial effects. For example, one can induce motion perception using static images [FAH91].

4.2 Visual thinking

Thought and perception have long been strongly distinguished. It was thought that perception, a passive mechanism, relays information to the conscious mind, which actually treats information. The difficulties of computer vision illustrate how wrong this was.

In fact, vision solves problems [Arn89]. It makes suppositions about the scene being watched, and it verifies them by "throwing" glances to the relevant areas of the scene.

Indeed, our vision is precise only in the center of our visual field, corresponding to the *fovea*. In order to explore the visual environment, our eyes continuously scan the scene (Fig. 20), with fixations of about 200ms [Sol94, DV00, vH25, Yar67, IBLK98]. The exploration path depends upon the scene, the conditions, and the goal of the observer [Yar67].

Vision is like scientific research. It proposes falsifiable hypothesis and verifies them by new observations [Gom56].illustrated in Fig. 21 (read also [Sol94]).

The reasoning of our visual system can be fooled when the scene does not correspond to our presuppositions about a "normal" scene. There is then *illusion*. The Ames room (Fig. 22) is a perfect example: since we assume that a normal room has orthogonal walls, two persons in this room seem to have surreal sizes.

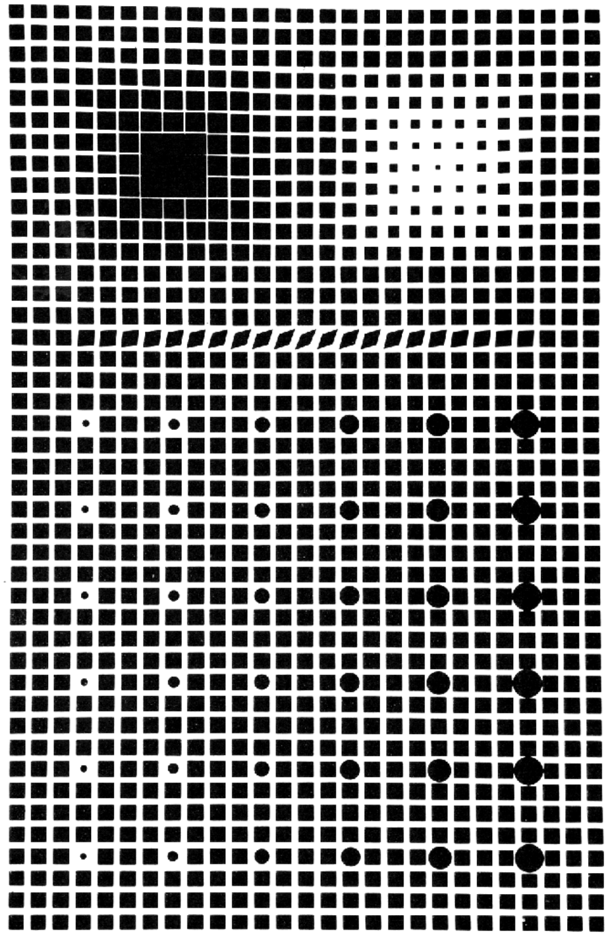


Figure 18: Victor Vasarely, a painter influenced by vision science. *Supernovae* (inspired by the Hermann grid).

Figure 19: Painting from the cave of Altamira in Spain, around 10,000 B.C.

Illusion is in fact not an anomaly of our vision, it just unveils the normal process of visual perception. Gombrich claims that illusion is the mechanism that explains the depiction power of images [Gom56]. When looking at a picture such as Fig. 24 , the change in our mental state that occurs when we switch from one interpretation to the other [Log00] allows us to better comprehend how we recognize a reality in a picture.

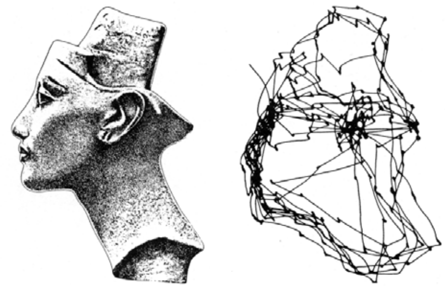


Figure 20: Exploration path of an image by the eye. From [Sol94, Yar67]

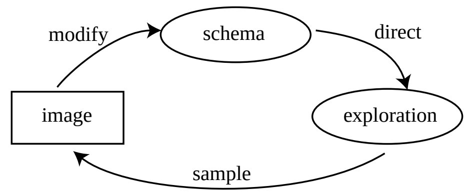


Figure 21: Neisser schema (adapted from [WH87]).

4.3 Invariants, constancy

One of the fundamental characteristics of our visual system is the ability to extract invariants from the constantly changing optical flow [Gib79]. The same object can indeed appear in very different conditions: luminous intensity, color of the illuminant, distance (and thus visual angle), view angle, etc. The size of the object, its shape, and its intrinsic color (reflectance) are some of these invariants.

We have seen that center-surround mechanisms make our visual system more sensitive to contrast than to absolute luminance. This is a crucial characteristic to extract invariants in different luminosity conditions.

Even better, our visual system seems able to decompose what we see into different layers of information: object reflectance, lighting, specular highlights, transparency, etc. [BT78, Ade93, Are94, Tum99].

We have here again a duality between the image reaching the retina and the extracted invariants. It is fundamental to wonder if the extraction mechanisms operate the same way when they analyze a picture and when they analyze the real scene. The power and

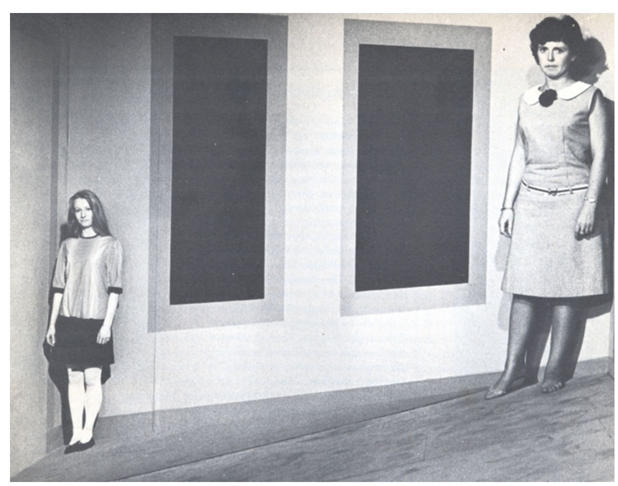


Figure 22: Ames room (from[GG73]).

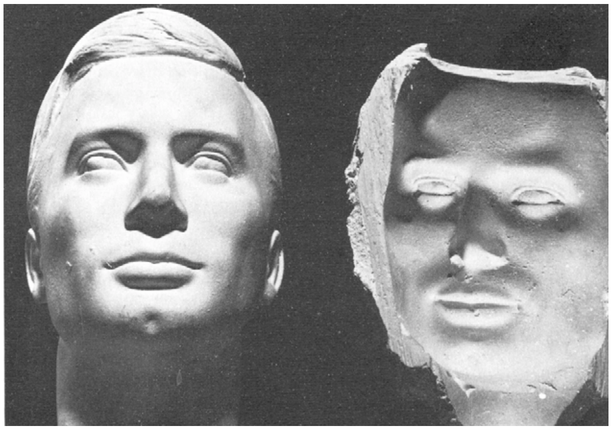


Figure 23: The negative face (on the right) appears positive (from [GG73]).

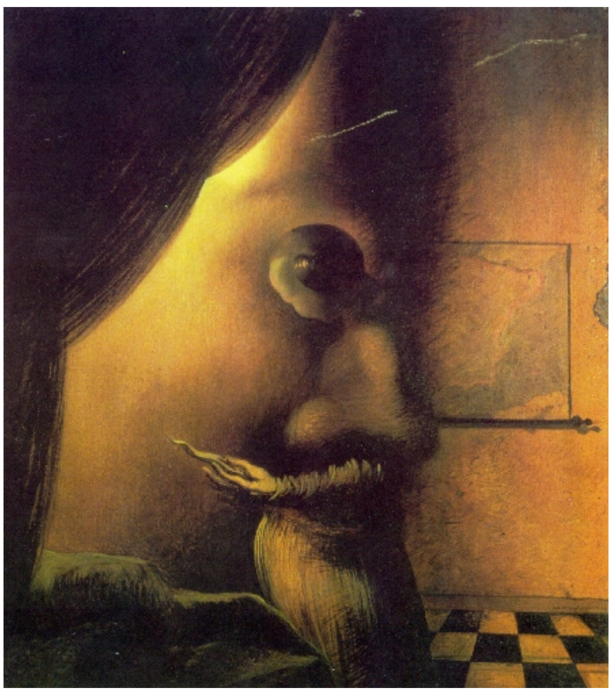


Figure 24: Illusion by Salvador Dali. The painting can be interpreted as the face of a man or as a young women in a bedroom.

limitations of pictorial depiction depend on the answers. If the extraction is shown to be different, the author of a picture can decide to compensate the deficiencies. This will be treated in Section 5.

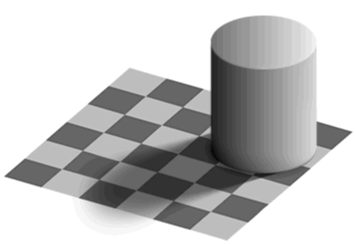


Figure 25: The white cells in the shadow of the cylinder have the same grey level as the black cells in full light. Illusion by Ted Adelson.

4.4 Perceptual level of visual representation

The thesis of Marr about computer and human vision [Mar83] have strongly influenced Willats [Wil97]. Marr's ideas are very polemical, but their importance can not be ignored. In particular, he has popularized the notion that vision is information processing.

Marr's theories are based on the translation from a viewer-centered representation (retinal image) to an object-centered representation (3D model). He distinguishes four levels: the retinal image (extrinsic observation), the primal sketch (corresponding to discontinuities are edges), the 2 1/2D sketch (containing depth, surface orientation and lighting) and finally the 3D model (intrinsic properties). This scheme can be found in most computer vision systems: image, edge detection, depth deduction (e.g. by stereovision, shape from shading) , inference of the 3D model.

Pictures can be interpreted through this scheme as well. Each picture style corresponds to one step of Marr's pipeline. Impressionist painting (Fig. 26) corresponds to the retinal image, line drawing corresponds to the primal sketch, Renaissance art would be more like the two and a half dimensional sketch and cubism would correspond to the 3D model.

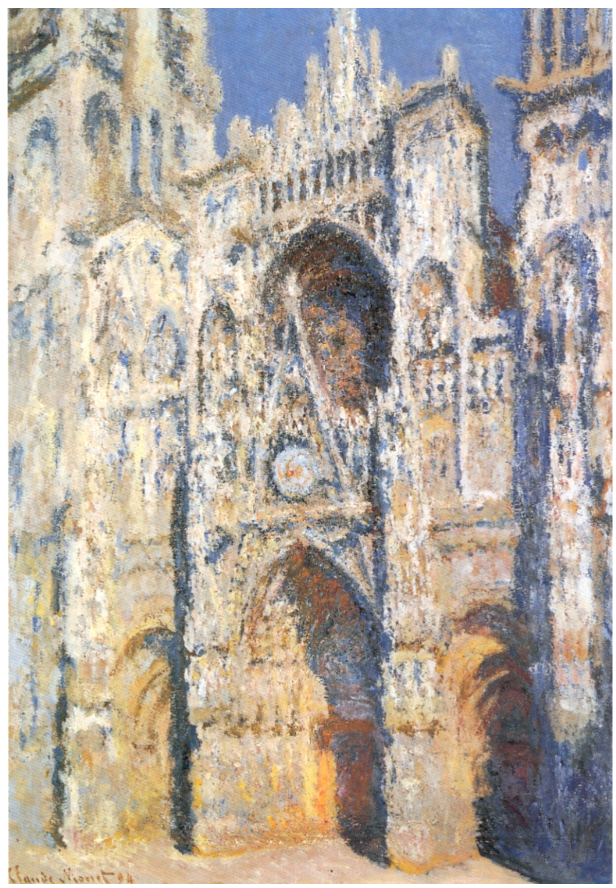


Figure 26: Claude Monet, *Le Portail et la tour d'Albane, plein soleil*, 1893-94.

This is also a scale from what we see to what we know. It is usually said that young children first draw what they know, then as they get older, they draw what they see. This classification also applies to colors, as will be discussed in Section 6.3. A color on the picture can represent the color of the light reaching the eye (radiance color) but also the reflectance of the object (color invariant).

Western art from the Renaissance to the Impressionists has focused on the extrinsic, neglecting the intrinsic, as opposed to oriental art for example. Chinese painting never depicts shadows, since they are only transient properties that do not belong to the true characteristics of the objects [Gom95a].

However, one has to keep in mind that the picture is also seen through the observer's visual system (Fig. 11). When we say that a line drawing corresponds to the center-surround edge detection (Section 4.1), we have to remember that these lines will also be analyzed by the center-surround filter. The issue is not simple.

5 The rich limitations of the medium

Be it oil on canvas, phosphor on a monitor, or graphite on paper, the medium imposes its physical characteristics that restrain representation. We borrow inspiration from the seminal lectures by Helmholtz [vH81], from Barbour and Meyer's study [BM92] and from Cowan's work [Cow95]. We underline these limitations and sketch some techniques used to compensate them.

5.1 The picture is flat

A picture is flat, which removes many depth cues: parallax, stereovision and accommodation. Other cues remain, such as occultation (but see Fig. 27), foreshortening (distant objects appear smaller), texture gradients, atmospheric perspective, and shadows [Sol94].

Figure 27: René Magritte *Le blanc-seing*, 1965.

In order to compensate the loss of the first category, the artist can choose to accentuate the second ones. The choice of a configuration where foreground objects occlude objects behind them will highlight the hierarchy of distances; a dramatic perspective with strong converging lines will emphasize the depth of the scene; the same is true for the gradient of a texture on a large object such as the ground (grass in Fig. 28, mosaic in Fig. 29); or for the modulation of the color or precision by distance (haze in Fig. 30, or depth of field or thicker lines for the foreground [Wil97]; finally, shadows help setting the spatial relationships among objects.

Figure 28: Claude Monet *Les coquelicots à Argenteuil*, 1873.

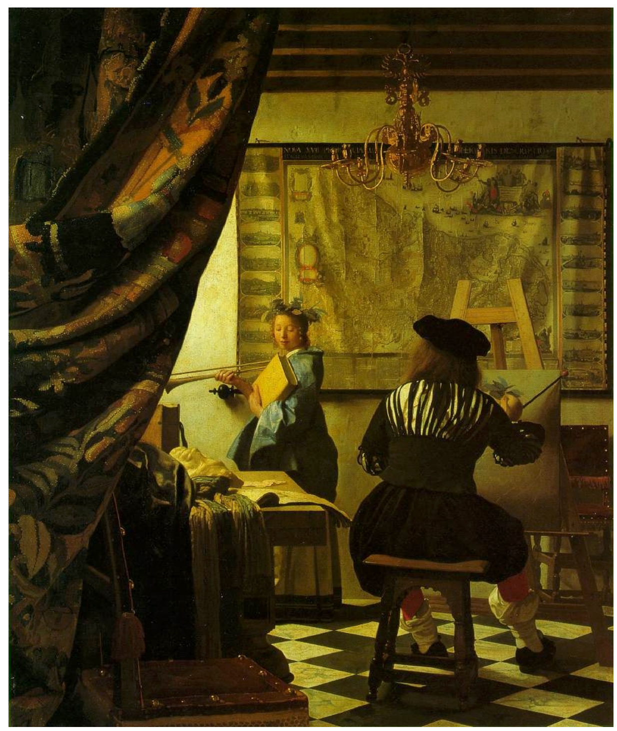


Figure 29: Vermeer Van Delft, *Le peintre dans son atelier*, 1666-1673

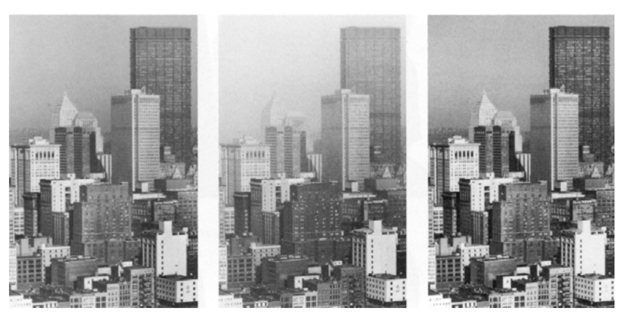


Figure 30: The use of filters permit the control of the amount of fog in black and white photography. Left:original image. Middle: the use of a blue filter increases the effect of haze. Right: A red filter removes haze. (from [Kod81]).

Other compensations can also be added. A first approach highlights the occlusions by accentuating the contrast at the silhouettes (by adding lines or by choosing contrasting colors for the occluding and occluded objects). Another approach takes example from atmospheric perspective and attempts to group objects of similar depth by assigning them similar properties (color, precision, style).

One of the major goals of cinema lighting is to model space [Mil91, Low99, AG99, Arn54]. It permits the accentuation of contrast at occlusions (the back light in Fig. 3 creates a highlight at the silhouette), and it allows “planes of light” to group objects by distance, by illuminating them similarly.

Figure 31: Titian, *Noli Me Tangere*, 1511. Note how the tone used to depict the houses is modified artificially to increase the contrast at occultation.

Traditional Chinese paintings represent mountains by a gradient, dark on top and lighter below. Since Chinese pictures use aerial views, the dark part of foreground mountains contrasts with the light part of background ones. Wang Wusheng has remarkably translated this technique to photography (Fig. 33).

5.2 The viewpoint is unique

At least conceptually, most images correspond to a single view, whose viewpoint (or its generalization) is unique. However, in the real world, we move to explore objects under every angle, we can solve ambiguities by changing our viewpoint (which is related to parallax discussed in the previous section).

The picture creator thus faces the problem of choosing this unique generalized viewpoint. The issue of accidental (or degenerate) or general view is important [Wil97]. This is related to the depth cue problems: a general configuration is more efficient at representing spatiality. This choice will strongly influence the competition between 2D and 3D aspects of the image, since an accidental alignment for example is a 2D property corresponding to no 3D property.

Some styles use diverging perspective that allow to show more facets of an object. Its is the case with Byzantine painting (Fig. 35)

Figure 32: *The Matrix* poster movie. The occlusion of the background character by the main character is enhanced by the contrast caused by the haze.

Figure 33: Photo by Wang Wusheng. Note how space is modeled by the contrast between mountains accentuated by haze. From the book *Himmelsberge*

and with some cubist works. Schaufler applies this principle for image-based representation [Sch99]. Ancient Egyptian art chooses the more relevant view for each part of the human body and composites them together (Fig. 34). This results in a strange pose if the image is considered as a Western perspective view. Cubism also uses an approach where multiple viewpoints are used and merged for one image (Fig. 37). See also the work by Rademacher [RB98] and Fig. 38. We will discuss these points again in Section 6.1.

Introducing mirrors inside the scene permit the conciliation of Western realism and multiple viewpoints [Mil98] (Fig. 39.

Figure 34: Stuc painting from the 18th dynasty.

Figure 35: Andrei Rublev, *The Holy trinity* (between 1408 and 1425).

5.3 The picture is finite, it has a frame

Most pictures are finite rectangles whose frames are visible. The information perceived through peripheral vision in the real scene is lost in the picture. As the choice of the viewpoint, framing is fundamental for the meaning of the image [Ber72].

The presence of the frame can highlight the 2D nature of the image. It also provides cues for the mechanisms that compensate distortions occurring when the image is viewed obliquely [Hag80, BM92]. In addition, frames also provide references for the perception of horizontal and verticals, hence the importance of compensating for converging verticals in architecture photography.

A cut occurs at the edge of the image. Depending on the choice of the author, it can be more or less abrupt, potentially truncating important objects (Fig. 41). It can reinforce the vision of the picture as a window on a reality.

Figure 36: Photo with diverging perspective (observe the top and bottom of the vase). André Kertész, *Melancholy Tulip*.

Figure 37: Pablo Picasso, *Femme assise dans un fauteuil rouge*, 1931. The face merges aspects from a profile and front view.

In the 19th century, vast panoramas allowed spectators 360 degrees views (Fig. 43). Nowadays, IMAX movie theaters, CAVEs [CSD93] and Quicktime VR offer similar filed of views. Chinese handscrolls also offer a wide field of view (Fig. 44).

(a) (b)

Figure 40: Framing changes the subject of the image. (a) Boticelli, *Venus and Mars* (allegory). (b) The detail becomes a portrait (after [Ber72])

Figure 44: Yuan Jiang, *Garden for gazing*, China, Qing Dynasty, 1690-1746. The orthographic projection is more suited to the particularly wide format of handscrolls.

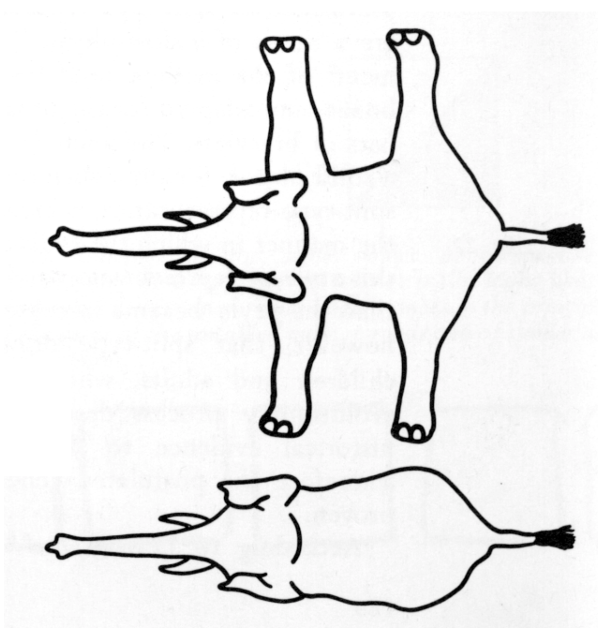


Figure 38: Hudson's elephants. During a multi-cultural study, African subjects preferred the topmost elephant, while European subjects preferred the bottom one. Note that the topmost view actually renders the structure of the elephant better (from [GG73]).

5.4 The image is static

When it is not animated, a picture is static[1]. The author not only has to choose the viewpoint and framing, but also the moment and all its implications.

[1]Lord la Palice, personal communication.

Figure 39: Diego Velasquez *Venus au miroir* 1649-51

An author who wants to depict a dynamic scene on a static picture has different solutions [Hag80]. The subject itself can suggest motion, such as a plane in the sky. The pose can obviously represent a phase of a movement, especially when it looks off-balanced (Fig. 45). The image can also superimpose successive time steps, or a sequence of images can be put next to each other (Fig. 49); stroboscopic photos are a good example (Fig. 46). Other methods exist: motion blur (Fig. 47 and 48), the addition of lines in the direction of motion, or more symbolic glyphs, such as arrows. Comics are a paradigm for the use of all these techniques.

The motion can also be rendered by a lack of balance in the 2D composition [Arn54]. The asymmetry of the image can then "attract" the subject to the empty side, or oppositely, suggest that it is coming from this same empty side (Fig. 51).

Figure 50: The adventures of Calvin and Hobbes by Bill Watterson (from *The days are just packed*). Most of the motion rendering techniques are used here: multiple positions (top-left) motion lines and motion blur of the background (middle-bottom) unbalanced positions, subjects cut by the frame (top right).

Figure 41: Edgar Degas, *L'école de danse*, 1874.

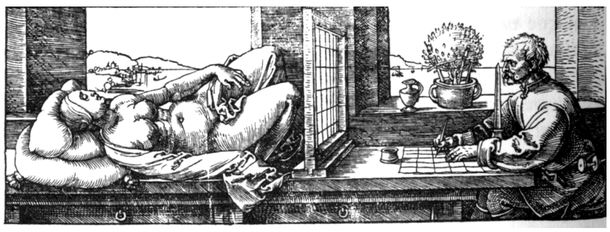


Figure 42: Metaphor of the window illustrated by Dürer.

A more original approach consists in exploiting the characteristics of our perception of motion to stimulate it directly with static images [FAH91].

5.5 A limited contrast

The human visual system can operate over a large range of luminous intensity, from $10^{-6} cd/m^2$ to $10^6 cd/m^2$, and scenes exhibiting a contrast of 1 to 100,000 at a given time are common. Unfortunately, commonly used media offer at best a contrast of 1 to 300 [Hun95, Ada95, Tum99]. A picture thus has to compress this contrast, potentially attempting to preserve brightness impression and details in both dark and light parts of the scene.

The fact that our visual system is sensitive more to local contrast

Figure 45: Théodore Géricault, *Course de chevaux à Epsom*, 1821.

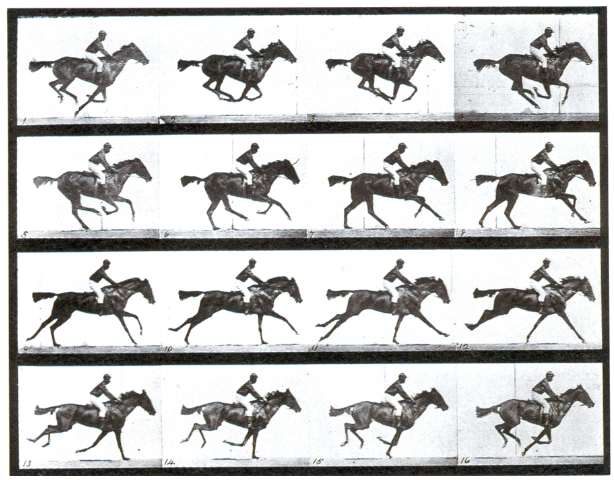


Figure 46: Eadweard Muybridge, *Galloping horse*, 1872. These images showed the error of Géricault and others: a horse never has all his legs spread in the air.

than to absolute luminosity helps a lot. Moreover, the ability of our visual system to separate illuminance information from reflectance can also be unconsciously used by painters to decrease the huge contrast due to the illumination [Tum99].

Photographic films have an S-shaped response that is quasi linear

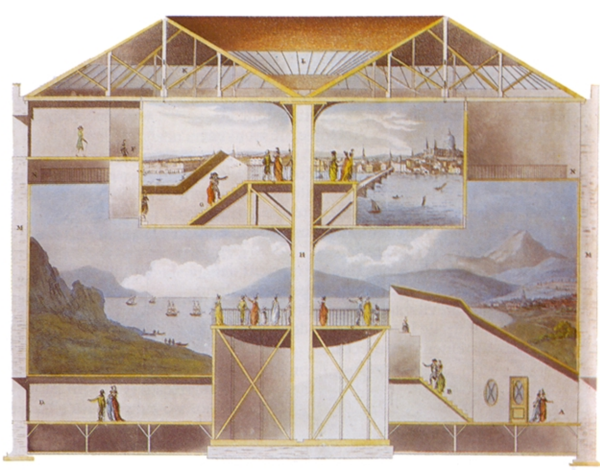


Figure 43: A panorama in the 19th century [Com92].

Figure 47: Diego Velasquez *Las Hilanderas (the spinners)* 1657. note the motion blur of the spinning wheel.

Figure 48: A special filter (on the right) permits the simulation of motion blur (from [Kod81]).

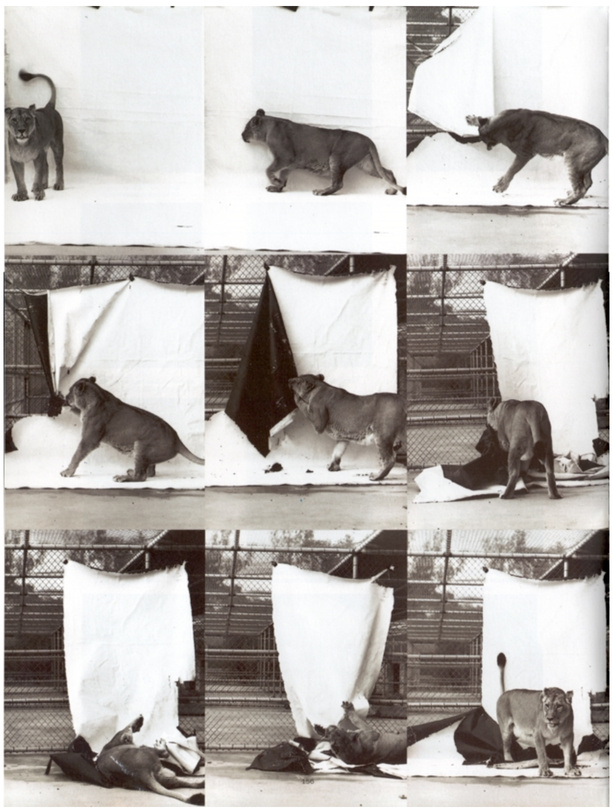


Figure 49: Gary Heery *Lion, panthera persica X L leo* (from the book *Zoo*).

in the medium tones, but provides a smooth compression for high and low tones.

The addition of flares and halos permits to increase the subjective brightness of light sources and bright areas in the picture [SSZG95]. Photo and cinema lighting aims at managing the contrast of the scene, particularly by subtly illuminating the areas in shadow (fill light in Fig. 3) [Mil91, Low99].

Moreover, pictures are usually watched in conditions that are different from their corresponding real scenes; and our perception of brightness is not linear, it depends on the surrounding luminosity. Brightness contrast is decreased in a dark environment, which has to be compensated using γ correction: the medium part of the tone reproduction curve of film is actually not linear, it is a power function with exponent γ.

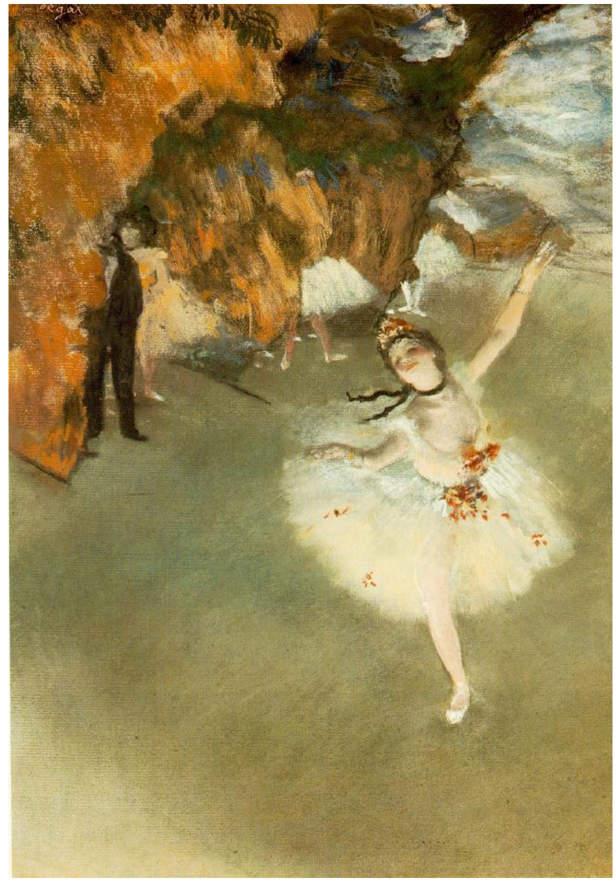


Figure 51: Edgar Degas, *L'étoile*, 1878.

5.6 A limited gamut

The available color gamut is also often limited. The palette of painters has improved over the ages [DG00]. Simultaneous contrast help reinforce the saturation of colors by putting contrasting colors close to each other [Roq00]. In computer graphics, the technique of *gamut mapping* consists of optimizing the use of a limited gamut, especially when transferring files among different devices and for printing.

It is well known that the color of different light sources varies. Our visual system is able to cope with this through chromatic adaptation, which allows us to discount the chromaticity of the illuminant. This is crucial for color constancy. However, when looking at a picture, our visual system adapts to the illuminant of the surrounding real world, not to the illuminant of the depicted scene. Hence the need to compensate the color of the illuminant when creating a picture, and the existence of different films for outdoor and incandescent conditions, or the use of filters to compensate (Fig. 52).

6 Representation systems

We now try to formalize the techniques or systems of representation, that is, tools or elements of style that come into play when reality is represented on a 2D medium. The two first sub-sections are largely based on the book by Willats [Wil97]. Read also the text by Riley on the subject [Ril00].

Whether these techniques are based on acquired conventions or innate characteristics of our perception is still a hot issue, which we will not really address (see e.g. [Hag80, GG73, Ril00] and Fig. 38).

Figure 52: Photo of a scene illuminated by neon light. (a) With no correction. (b)With correction filter (from [Kod81]).

The great strength of Willats' thesis is that it is not limited to classical visual arts, it also applies to oriental art, modern art, technical illustration, cartography, and any 2D representation of reality. It is largely based on experiments with children of various ages. Just as illusion permits us to work out the limits of our perception, studying the development of children sheds light on distinct processes that are not developed at the same age.

Based on Marr and Nishita's work [MN78], Willats [Wil97] distinguishes two elements in representation: the drawing system and the denotation system. The drawing system (which can be understood as projection system) deals with purely geometrical and projective aspects of the image. The denotation system handles the 2D primitives (lines, points, regions) used to depict the 3D scene, whatever their position We will add a tone system that deals with tones and colors, and we will discuss the relation of these systems with style.

6.1 Projection system

The most familiar projections are linear perspective, orthographic, oblique (Fig. 44 et 53), axonometric, and isometric. Divergent perspective is common in Byzantine art (Fig. 35) and by cubist artists, who also use very complex systems of projection where many viewpoints are merged. They even sometimes borrow inspiration from non-Euclidean or 4D geometry [Hen83]. These non-classical perspective have also been proposed in computer graphics [Grö94, BFR95, Lev98, AZM00].

Figure 53: Photo by Wang Wusheng, from the book *Himmelsberge*. Wusheng's photo respects perfectly the canons of ancient Chinese painting: aerial view, oblique perspective.

Linear classical perspective is unquestionable (for realism) only if the picture is viewed from the viewpoint corresponding to the virtual viewpoint. Otherwise, distortions occur due to the double application of perspective laws, as illustrated by photos of photos. Mechanisms of our perception compensate most of these distortions [Hag80], but the relation between projected image and 3D scene is far from simple.

For projections, Willats insists on the difference between the primary geometry (in object space) and secondary geometry (in image space). We are more accustomed to primary geometry (viewpoint, direction of projection) and its extremely compact expression in projection matrices. However, art functions more in terms of secondary geometry, which moreover allows the description of a wider class of projections. Some systems are very different from perspective and aim at representing the topological relations among parts of the scene.

Secondary geometry can be seen as a set of rules: foreshorten distant objects, make parallels converge, project circles into ellipses, etc. This is typically illustrated by perspective books. The description obviously becomes longer, but allows more variations. Indeed, each rule can correspond to one aspect of our perception of space, and it can be important to include them selectively, for aesthetic reasons or for efficiency. For example, one can wish to represent distant objects smaller, but use an orthographic view for each object.

As it is the case in art history and art manuals, it is then very important to distinguish between one-point perspective, two-point and three-point perspective, though they all correspond to the exact same primary geometry. However, if one refers to the property of projected objects, one-point perspective preserves rectangle parallel to the image plane, two-point perspective preserves vertical lines, while three-point perspective distorts all the canonical lines. Of course, this all depends on the geometry of the objects of the scene and their canonical frame. One can also see here a transition from the dominance of 2D properties (some 3D rectangles are actually rectangles in 2D), to a more purely 3D picture. And remember how special vertical and horizontal line can be in the picture, because of the presence of the frame.

In fact, we propose that the systems of projection and their secondary geometries can be seen as the satisfaction of a set of constraints. This extends Willats' ideas [Wil97] and Zorin's presentation [Zor95]. The constraints describe the interaction between 2D and 3D aspects of the image, and human perception. Examples of constraints are: straight lines in 3D should be represented as 2D straight lines, 3D distant objects should appear smaller in 2D, near objects should (or should not) occlude more distant ones, as many facets of the object as possible should be represented, a 3D sphere must be represented by a 2D disk, etc. These constraints are obviously related to the limitations of the medium and their compensation (see previous section).

Linear perspective is a simple and elegant solution that satisfies many of these constraints (alignment, foreshortening) but fails for others (spheres are projected as ellipses, there are distortions for wide angle views). The use of tilting lenses for architectural photography corresponds to the preservation of verticals constraint.

Note that the set of constraints does not only influence the projection operation, but also the viewpoint or the placement of objects in the scene itself. For example, a group photographer will ask people to move to have a better composition and see everyone.

Moreover, as opposed to Zorin's approach [Zor95], these constraints need not necessarily be global, for any possible scene (which greatly limits the solutions), but can come from the only objects of the scene, or selectively to each object. For example, it is not important that all possible lines project as lines, but that the line segments of the scene are projected onto lines, or maybe only some particular lines are important and should be preserved.

Egyptian art uses local constraints to optimize the aspect of each part (Fig. 34 and 54). Folk American art presents similar characteristics (Fig. 55).

Figure 54: *Garden of Nebamon*, around 1400 B.C., painting on a wall of the tomb in Thebes. The projection respects individual constraints where the 2D aspect is paramount: the 2D trees are perpendicular to the pond, the 2D pond is a rectangle, the fishes are represented in a profile view where they are more recognizable.

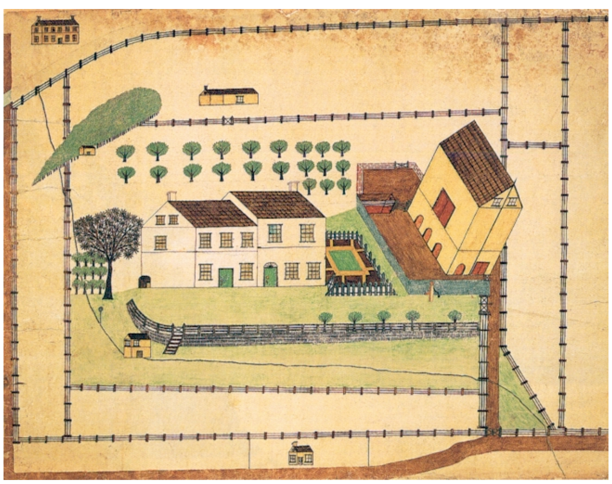


Figure 55: Unknown artist, American, beginning of the 19th century, *Pennsylvania Farmstead with Many Fences*

The art of M.C. Escher shows striking examples of a perspective that is absolutely not linear, but that satisfies most of the constraints related to linear perspective (Fig. 56).

The School of Athens by Raphael ((Fig. 57) presents an example of perspective that is not completely linear, despite the very classical Renaissance perspective used for most of the scene. The sphere on the right is represented by a disk, not by an ellipse [Pir70, dLG59]. The intrinsic properties of the object (roundness, symmetry) and their direct translation into 2D have overruled the primary geometry of linear perspective.

The artist can also purposefully choose a visually inconsistent projection system. Some authors believe that divergent Byzantine perspective was used in order to avoid realism and thus idolatry [Wil97]. Surrealist painters wanted to dismantle space. In the case of de Chirico, the use of different viewpoints for each part of the scene imposes a malaise (Fig. 59) [Arn54, Wil97]. Projection constraints can also come from non geometrical issues: the 2D size of characters can be related to their rank or importance. It is the case in Egyptian (Fig. 34) or Middle-Age art, but also for many move posters (Fig. 58).

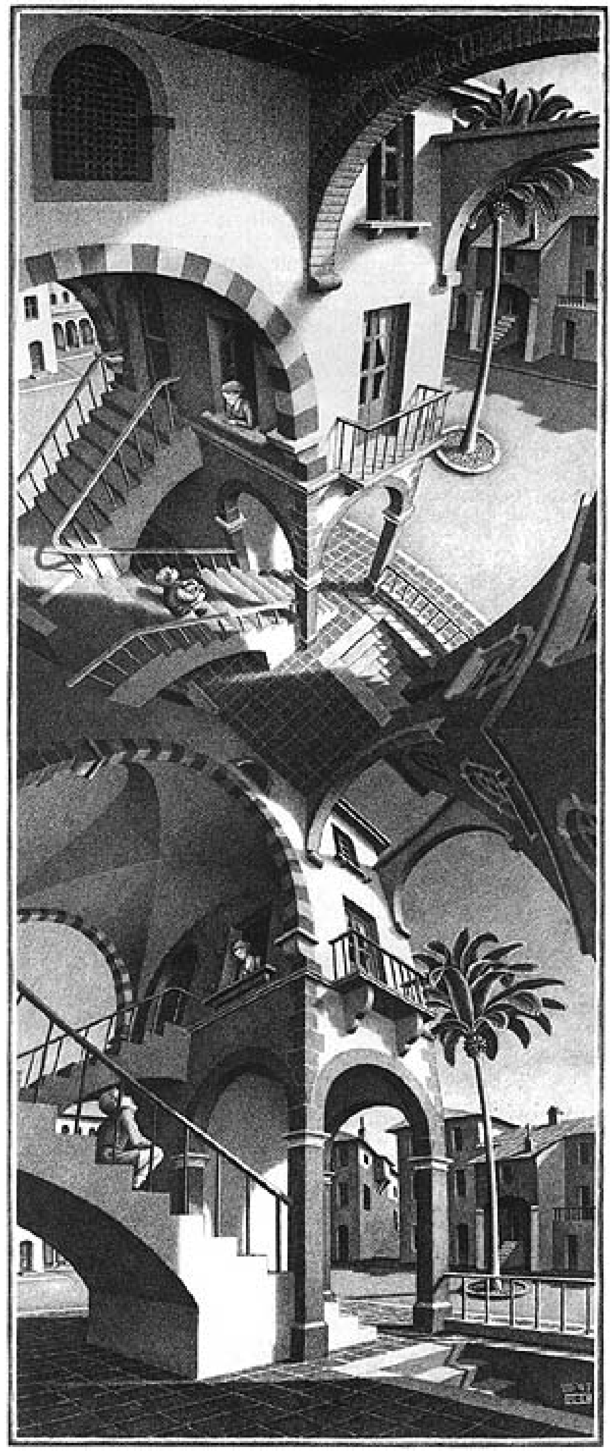


Figure 56: M.C. Escher *High and Low*.

The problem of projecting a 3D scene onto a 2D picture is in fact over-constrained. It is not possible to satisfy all the "desirable" properties. Consider the example of two horizontal lines parallel to

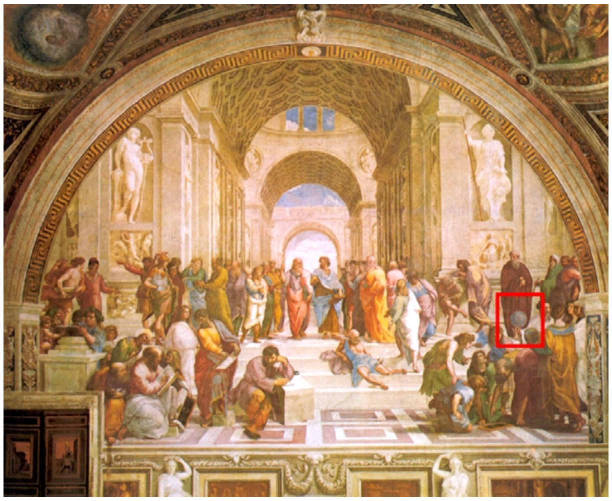


Figure 57: Raphael *The School of Athens*. The sphere in the red box should be projected as an ellipse in pure linear perspective.

Figure 58: Poster of *Gone with the wind*. Note how the size of various characters or scenes does not depend on perspective rules, but on their importance.

the image plane (the top and bottom of a wall for example). Linear perspective will project them onto two parallel lines on the image. Each line is projected onto a line, and parallelism is well rendered. Visually, however, the visual angle sustained by the wall decreases on the two sides, since the portions of the wall are more and more distant. This is obvious if we turn the camera to one side: the parallels will converge. When we visually explore the scene with our ocular movements, the two parallels converge on both sides. This

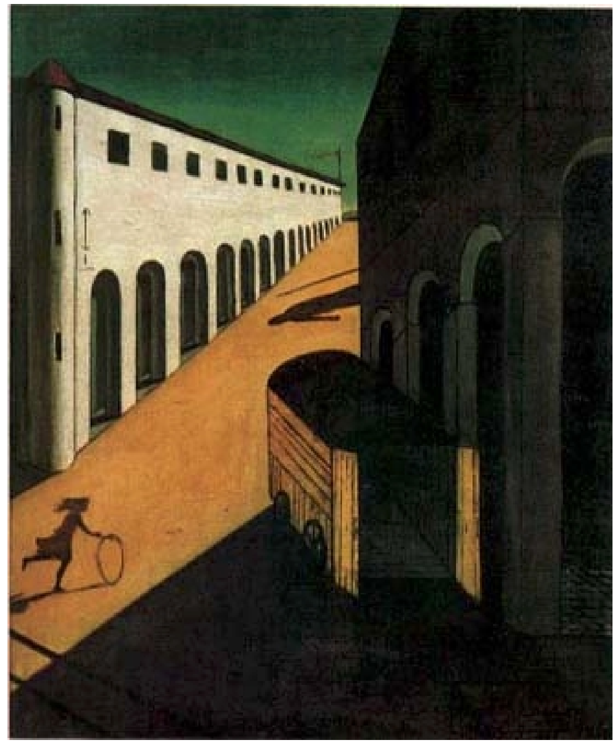


Figure 59: Giorgio de Chirico *Mystery and melancholy of a street*.

property is not compatible with the projection of each line onto a line (however, see Fig. 61 and 60).

Figure 60: Jean Fouquet, *Arrivée de Charles IV à la basilique de St Denis*, 15th century. Note the curvilinear perspective, as if the painter had followed the arrival of the king by pivoting his gaze [Com92].

This fundamental impossibility to respect all these desirable constraints and the paradox implied lie at the base of most quarrels related to perspective. It is also one of the great wealths of visual arts (just as the impossibility to devise a perfect scale is one of the wealth of music).

6.2 Denotation system

Willats [Wil97] proposes three classes of denotation systems, depending on the dimensionality of the 2D primitive they use. We illustrate them with three works by Picasso (Fig. 63). The silhou-

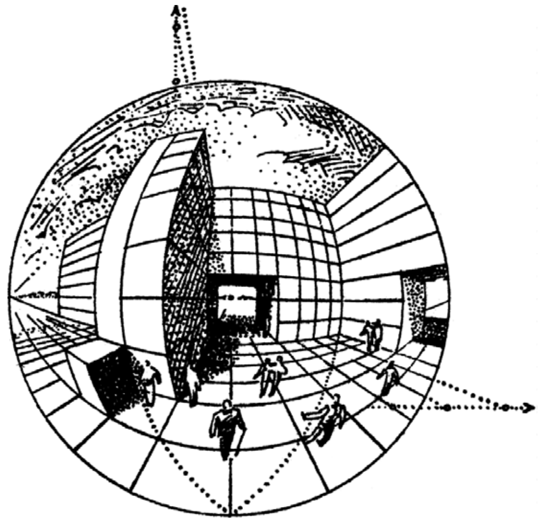


Figure 61: Curvilinear perspective using Flocon and Barre's technique [FT63].

Figure 62: Two views of a Termesphere by Dick Termes representing the inside of a cathedral.

ette system uses regions as image primitives. Line drawing uses lines or segments. As opposed to the previous one, it not only represents borders between different objects but also internal contours. Finally, the optical system uses points whose color can depend on the optical properties of the scene. However, he does not claim that these colors are necessarily a representation of the optical flow coming from the scene. We will discuss this point in the next sub section.

These systems are related to the aforementioned perceptual categories of Marr.

Willats insists on the difference between *primitives* and *marks*, which are the physical entities used to render the primitives. In particular, the shading obtained by hatching uses 1D marks (lines), but belongs to the optical system because each point of the image has a different perceived tone obtained by a perceptual fusion of the marks.

This classification can also be related to the writings of Wölfflin [Wöl50], in which he describes a difference between lineal and pictorial style. However, the similarity is far from perfect and highlights the non exclusivity of the systems. *The School of Athens* by Raphael (Fig. 57) would be considered by Wölfflin as lineal (the line drawing dominate and rule the painting, different regions are clearly separated as opposed to a painting by Rembrandt or by the Impressionists where only the brush strokes are visible), while Willats would classify it as optical (the scene is rendered by the use of different colors for points of the picture).

6.3 Tone system

We believe that it is useful to add a third system, the tone system, which describes the color and intensity of the primitives of the scene. For Willats, the question arises only in the optical denotation system. However, the color of a line can depend on the shading of the object, and regions in silhouette denotation also need a color. Note that we also include here the thickness of lines, which contribute to the perceived tone.

For "realistic" pictures, tone will depend on the optical flow determined by light transport and light-material interactions in the 3D scene [CW93, SP94, Vin89]. One can then distinguish shading, cast shadows, self shadows, and atmospheric effects. The tone can also represent the intrinsic color of the object (reflectance), be symbolic (such as in Middle-Age or Byzantine art), simply represent the importance of the character, or being driven by 2D aesthetic reasons (harmony, enhance the contrast), contribute to the ambiance, respond to clarity constraints or conventions (technical illustration), etc.

Cinema lighting (Fig. 3) can be seen as a bypass of the purely realistic tone system. The placement of light sources allows the control of contrast, highlights important characters, sets the mood, etc. It is interesting to realize that this lighting bypasses the physical conditions and constraints offered by reality to emulate some effect developed in painting. Is it thus relevant to use ever more physical simulations in computer graphics, which reintroduces undesirable constraints [Bar97, AG99]?

In black and white photography, in addition to tone reproduction and masking techniques [SCCZ00], the photographer can use color filters to control the tone system (Fig. 30 and 64).

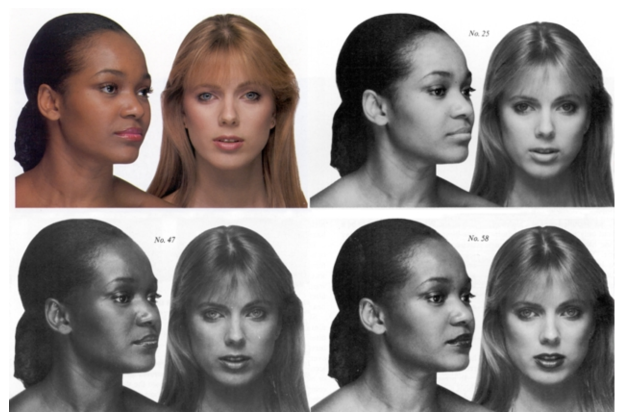


Figure 64: Influence of color filter on black and white photography The three black and white images show the effect of different filters on the faces represented in color (from [Kod81]).

6.4 What is style?

The definition of styles and their evolution is at the heart of art history. However, it is only in the 20th century that systematic approaches appeared, as well as classifications that do not rely on a single scale related to realism. [Wöl50, Gom56, Wil97]. At a different level, computer graphics becomes interested in the separation of style and content [FTP99, TF97, HS99, BH00].

Style includes temporal, geographical and personal aspects. We will separate the subject from the style. It is clear that different artists, different places and different eras have been interested in different subjects, and that these differences are crucial for their study. Nonetheless, it has to be differentiated from the way a given subject is chosen to be depicted. The borderline may be tenuous, it is however of importance.

(a) (b) (c)

Figure 63: Pablo Picasso (a) *Rite of Spring* (silhouette). (b) *Portrait of Igor Stravinsky* (line drawing). (c) *Paul en Arlequin* (Optical denotation).

We cannot claim to be able to give an answer to a question that has haunted and fascinated art historians and art psychologists for decades. We just try to draw some objective aspects or style, starting with Willats' categories [Wil97]. We hope that this discussion can help establishing a clearer framework for the non photorealistic rendering field. We are interested in an extended notion of style, encompassing not only artistic pictures, but all kinds of pictorial representations.

The choices related to the three systems described above are of course a first element of style. Each system naturally defines a set of characteristics of style (choice of projection, viewpoint, size and shape of strokes, brush, filling pattern for regions, inclusion of some optical effects, etc.)

Transversal to the above elements, the amount of detail or acuity or precision is a fundamental aspect of style. It can help in shaping space, it can guide the gaze, or choose a level of abstraction. Often, the loss of details will be obtained through larger marks, the brush stroke will be more visible and the 2D aspect of the picture will become more prevalent over the 3D reality (Fig. 65). It also stimulates the viewer's imagination. And since our vision works by checking hypotheses, the absence of details that could infirm hypothesis favors the most spontaneous interpretation of the observer. This brings a lot of the picture's beauty into the eyes of the beholder.

Style also contains purely 2D aspects, which rule the balance and composition of the picture. Gestalt psychology is to date the most powerful tool to formalize them [Arn54, Zak97].

All these elements interact during the elaboration of style. Some combinations seem more harmonious, other will deliberately shock. This essay has only skimmed over the articulation of these components and their motivations, but nothing that would permit understanding the essence of styles. We have only sketched the vocabulary of style, its grammar and semantics remain to be explored.

Figure 66: Victor Vasarely*Figure-ground reversal* (inspired by the figure/ground problem in Gestalt psychology).

7 As a conclusion

The production of image can be motivated by very different functions, that will lead to very specific constraints, that a single technique cannot satisfy. A religious image is not made like the manual of a vacuum cleaner, the visualization of statistical data or a physical lighting simulation.

The picture creators before us have developed a great wealth of techniques who all have their qualities, their domains of application. We should take inspiration from these to create images that are more functional, more aesthetic, more suitable.

"Vous voulez que je vous dise ce qu'est l'art ?
Si je le savais, je le garderais pour moi."
Pablo Picasso

Acknowledgements

I thank Julie Dorsey who supported this research. Victor Ostromoukhov got me started and accompanied me on these fascinating subjects. The syllabus of Marc Levoy's class was the initial inspira-

(a) (b)

Figure 65: Variation of the amount of details in Rembrand's portraits. (a) Self-portrait painted in 1629. (b) Self-portrait painted in 1661. Also note how, in the second painting, the concentration of details attracts the gaze and gives a vibrant life to the picture.

(a) (b) (c)

Figure 67: Vincent Van Gogh. *La maison jaune (La maison de Vincent)*, 1988 (a) Quill and China ink. (b)Watercolor and reed. (c) Oil on canvas.

tion and the reference of our early discussions. Thanks to Clairette Auriault for the example of the church. Xavier Decoret first introduced me the idea that image synthesis is illusion. Thanks to Raph' and Cati to help me improve my bibliography. Thanks to Max Chen for checking my English.

I dedicate this text to the memory of Alain Fournier, who opened my eyes and showed me that an image is more than a simple array of pixels.

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