1

Defining the Field of 2.5D Printing

1.1 What is Texture?

What is the relationship between textures we see in the real world and as a reproduction? How convincing are these? As more images are digitally reproduced and printed, standardised methods may result in a uniform ubiquity, whereby prints, posters, photos and reproductions of paintings are all printed in the same way, and likewise objects that are fabricated using the same materials, using the same layer upon layer fabrication methods. On the one hand, we can say that digital technologies have assisted in printing things faster, cheaper, bigger, bolder; on the other hand, we could suggest these things fall short of expected levels of quality. We could suggest that quantity may have been achieved at the cost of quality or ubiquity at the cost of diversity. In our manufacturing world, as more and more things are designed and created digitally, how do we bridge the gap between images we see on screen and how it is physically reproduced?

Texture can be described as the microstructural details that can be perceptually distinguished from one surface property to another. One could consider texture as multisensory; we only need to look at a surface to gain a quick understanding of its textural properties, which may then be reinforced by other senses (smell, taste and touch) (Klatzky and Lederman, 2011). Texture could be broadly categorised according to whether it is tactile or visual, it can be described by its appearance, as a noun or adjective and by comparison or difference.

Tactile texture. Tactile or physical texture describes the minute variations in the surface elevation created by the changes in orientation, density and distribution of tiny particulates of the surface. At our most primitive level and from birth, we engage with the world as a tactile experience and by using all our senses, we are compelled to touch materials, surfaces and objects to find out whether they are smooth or rough, soft or hard, or understand their material properties, for example, by handling a fabric to discern whether it is flexible or stiff or how it drapes. As a survival mechanism, it is highly important to recognise whether a food appears rotten (discoloured, wrinkled, mouldy) or whether an object may do us harm (prickles, barbs, spikes) (see Figure 1.1).

Visual texture. Visual texture usually refers to flat changes on the surface, a sort of drawing that demonstrates certain properties of periodicity and colour but does not present topographical

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Figure 1.1 Texture is useful for recognising the difference between something fresh and rotten (courtesy: Grace Parraman).

changes. For instance, a plastic table designed to look like wood may appear to be wood at a first glance (visual texture) as the drawing or projection of a picture is presented to be real wood, but may not feel like wood to the touch (tactile texture). We may miss the minute ridges, the roughness/smoothness of the material or the feeling of warmth. On a perceptual level, we use our library of knowledge to quickly recognise and chose from the range of materials and textures, and from a priori experience we no longer need to touch, for example, tree bark, velvet, brick. We can begin to order materials, for example, according to roughness or gloss. We can differentiate between the properties of materials or discern their suitability for a particular application, for example, different roughness, weight or pliability of a paper, or whether a shiny material is made of plastic or glass. Likewise, from our knowledge of handling fabric we can begin to use these for different garments.

Appearance of texture. In order to represent different textures or demonstrate an object's material qualities, it is important to render with convincing likeness. Artists have sought to paint and draw realistic representations of material surfaces and objects for hundreds of years, and now, through computer modelling, textures can be created virtually, whereby objects can be rendered for a wide variety of applications (film, animation, games, architecture) and bodies can be dressed in garments that drape and move in a lifelike way.

Taxonomy of texture. Using our skills to compare different textures, we are able to sort, categorise and name the appearance of a wide range of materials; some terms may be specific to different trades, subject areas, cultures and countries. From this, we have developed a rich vocabulary of adjectives to describe the differences and nuances of appearance (rough, smooth, prickly, slippery, slimy) or to describe their chemical or mineral appearances (gold, copper, granite, limestone) and material properties (denim, silk, wood, leather).

1.1.1 How to Quantify Texture

How may one quantify the appearance of a texture – by its characteristics or material properties? Some terms have different connotations depending on subject specialisms and requirements. Analogous to the many colour models that have evolved to suit different requirements, specialists and industries have developed their own quantitative methods – scales, comparisons and measurements – to define the parameters of manufacture or appearance and assist in selection, for example, roughness through the International Roughness Index (IRI), surface qualities of metals (R) (Black and Kohser, 2011), measurement of different aspects of the gloss of a surface (Hunter) Gloss Units (GU) or the dynamic viscosity of a liquid (centipoise cP). In commercial specifications it is sometimes easier to predict the behaviour of a material by comparing its material properties to well-known materials. For example, a manufacturer of adhesives, in approximating the viscosity of different products to a client, might achieve this by suggesting different domestic fluids and foodstuffs as a comparison: at 300 000 cP toothpaste is a highly viscous material that does not move without being squeezed, whereas a syrup at 4000 cP can be poured or dripped, and water has a low viscosity at 1–3 cP, and can be easily poured.

1.1.2 How do Artists Convey the Appearance of Texture?

Since the beginning of art history and throughout the centuries practitioners craftspeople, artists, designers, engineers and technologists – have been fascinated by the material they use, and by selecting different materials and mediums are able to translate meaning and concepts into form. A visit to any museum may well demonstrate a diversity of historical artefacts, each created using different tools, and each designed to achieve a specific mark. Over time, makers have developed different craft skills and tacit knowledge of materials, tool and techniques, and this knowledge passed down through workshops and studios.

The relationship between two and three dimensions is a long and enduring area of interest for technologists and artists. Artists have been constantly fascinated by the pictorial representation of a three-dimensional world through the two-dimensional media of painting and drawing, and by employing drawing elements such as perspective, illusion, colour, texture, light and shade to create more convincing and immersive environments.

Over the last one hundred years, photography and photomechanical processes have also played an important role in recording and reproducing images for mass consumption. Over the last few decades, sophisticated computer graphical interfaces have transformed methods of image construction, so that now we can no longer easily detect which components of an image are computer generated. Now we are presented with images that are ‘a plausible rendering of visual effects that create the illusion of life-likeness’. Surprisingly, this reference was made by art historian E.H. Gombrich (1909–2001) in his critique and analysis of the psychological aspects of image making (Gombrich, 1959, p. 246). Gombrich, most noted for his book *The Story of Art* (1950), also wrote prolifically during the latter half of the twentieth century on the arts and sciences. His writing demonstrates that our enquiry is certainly not new, but can be reappraised within this new digital context, namely of the development of surface fabrication and digital fabrication technologies.

So-called rapid prototyping and additive manufacturing technologies have shifted the technological focus from 2D inkjet printing to 3D digital printing, whereby a virtual object that has been generated and designed on computer can be exported and printed in layers to create a physical three-dimensional object. 2.5D printing, as an ad hoc and evolving technology, has borrowed elements from 2D wide-format inkjet and 3D digital printing systems. It has incorporated similar design workflow components to 3D printing, enabling printers to apply multiple layers of ink (and/or other materials) until a desired low relief elevation per layer, pixel or unit is achieved. The resulting surface could be considered either as a flat surface with some sort of topographic feature, or as a skin to wrap 3D objects.

Artists have created images using different mediums including stone, wood, paint and drawing as low-relief and two-dimensional narratives, scenes and pictures. From the perspective of appearance, materiality may also relate to the choice of material that an artist or a designer has chosen as a medium to transmit the experience of the image or artefact. In some cases, materials and media are selected for reasons of longevity, such as stone or wood, which may reinforce, challenge or confound the viewer’s perceptions of the artefact. As illustrated in Figure 1.2, the Italian sculptor Giovanni Strazza chose a hard, solid block of Carrara marble, which we would argue is the most inflexible and hardest of materials to convey the appearance of a diaphanous veil. However, Strazza has captured a translucency and

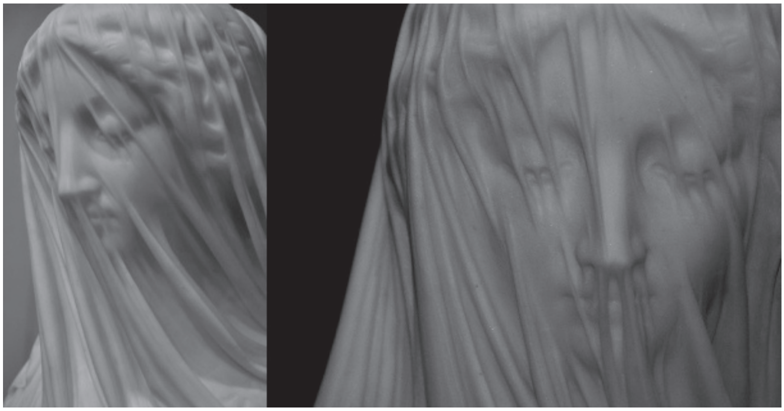


Figure 1.2 Giovanni Strazza (1818–1875) *The Veiled Virgin*, Presentation Convent, Cathedral Square, St John's, Newfoundland, a sculpture carved from a single block of marble (courtesy: Philip Chircop).

softness to the features of the woman's face and we can see through the close folds of the material and the braiding of her hair is also discernable. In this example, the hardness of the marble is at odds with the subject, and yet the artist has created a convincing appearance. Consciously we know the figure is not real, but by its verisimilitude we are moved by an aura of its emotional power.

1.1.3 How the Natural World Mimics the Appearance of Texture

We also find animals, insects and reptiles are excellent at using texture and colour to blend into their environment. Species around the planet depend on camouflage and mimicry for daily survival and communication. Animals have different ways of mimicking their surroundings. Depending on their needs, evolution has made some of them specialists in colour and others in physical texture. Chameleons may be considered the con-artists of the animal world, which can change the colour of their skins to blend into their environments, but there are many insects and sea creatures that are capable of even better illusions (Figure 1.3). For instance, the cuttlefish (not actually a fish but a cephalopod) is a master of

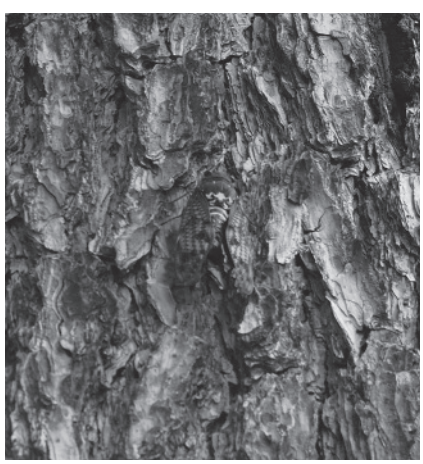


Figure 1.3 Cicadas in Japan blending with the textures and colours of their habitat.

disguise, despite assumptions of being colour-blind. Cuttlefish are known to have a diverse set of body patterns (colour, contrast, locomotion, posture and texture) that can switch almost instantaneously to adapt to their surroundings based on perceptual cues related to contrast, brightness, (micro) shape and visual and physical texture.

Humans have sought inspiration from them as a way of gaining insights into camouflage for re-creating patterns in fashion design or structures in architecture or biomimicry for electronic adaptive e-readers. In a study entitled *Biological vs. Electronic Adaptive Coloration: How Can One Inform the Other?* (Kreit *et al.*, 2012) developers of electronic reading devices of e-Paper have studied how cephalopods use subtle changes in their skin pigment to absorb or reflect available light. Technology based on 'emissive' light uses electrical fields in much the same way as cuttlefish.

These animals are able to mimic a wide range of colours and patterns that are highly convincing. However, we know when something appears right or wrong and are also very good at spotting differences and recognising patterns. Convincing texture reproduction and rendering tends to be more problematic, our visual system is able to pick out repeated elements (Figure 1.4) and we can discriminate

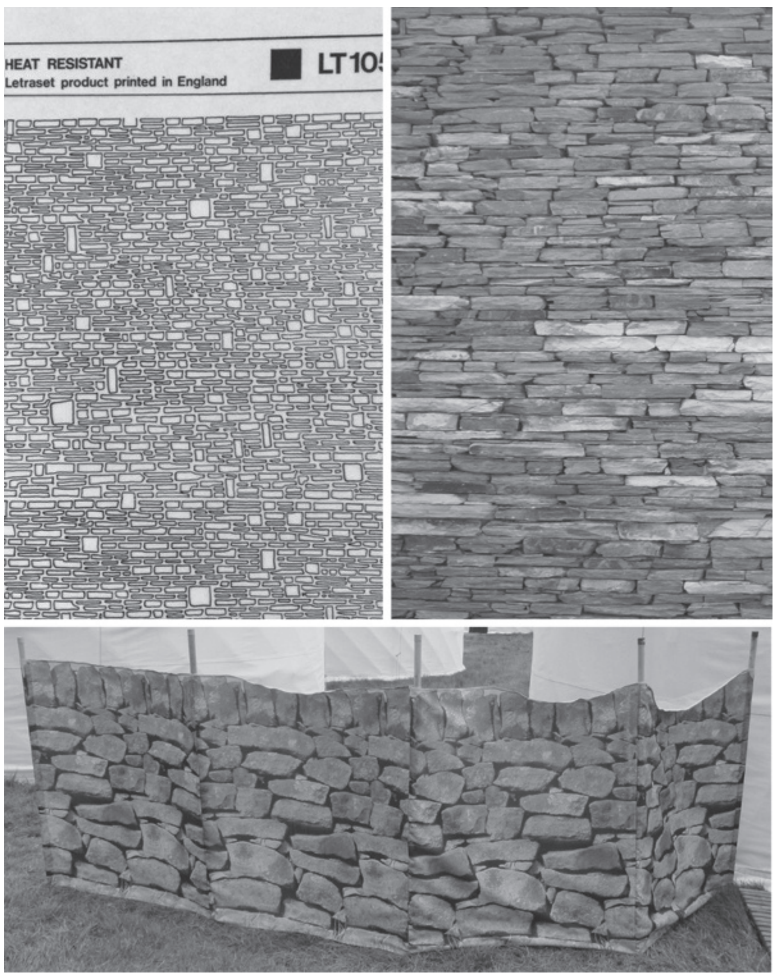


Figure 1.4 Left: sample image of a *Letratone* dry-transfer pattern of a wall traditionally used in graphic rendering. Right: an irregular pattern of a dry stone wall. Below a windbreak using a dry stone wall repeat pattern; note how the pattern is repeated for each panel.

the difference between natural and patterned texture. Likewise, a natural texture (grass, a brick wall, wood grain) appears homogeneous, but is infinitely random – each element is similar but remains unique. However, a patterned texture, although homogeneous, is composed of the same repeatable and recognisable elements (Hawkins, 1970). Furthermore, the effort in rendering surfaces with no discernable pattern structure comprising unlimited variations may result, as demonstrated by a computer-generated rendering, in exceptionally large file sizes. The new challenge for digital rendering is to investigate the relationship between the object and surface texture in a scene, and to render materials and objects where the textural attributes of the object are perceived to be convincing (Kim, Hagh-Shenss and Interrante, 2004; Adelson, 2001).

The complexity in the creation of a convincing textural render is essentially due to the enormous range of physical components that are required to incorporate all the nuances of a texture, such as colour, fibre, grain, reflectance, specularity, weave, hardness, softness, glossiness, fluidity and, as demonstrated in the previous list, the range of descriptive adjectives, cultural and specialist terms that extend these more subtle characteristics of a texture. Furthermore, these multivariables of textures tend to be stored as a visual taxonomy in the human memory, whereby subtle textures and surfaces can easily be identified and differentiated by our visual memory. In a real-world scenario, planed wood can quickly be distinguished from paper (grain, surface, flexibility), and animal fur from human hair (direction, colour, smoothness, curl).

1.2 Measuring Texture and Colour

How do we decide on a colour if a material surface is textured, and appears to contain a range of different subtle colours? How might we go about choosing a colour to paint a wall? For example, we may be inspired by bright yellow daffodils or wish to colour-match a plush red velvet sofa. Looking at the range of household paints in a DIY store highlights many subtle variations of colour, surface and texture. As consumers we are very exacting, we may leave the store with a pot of daffodil-yellow paint, yet when we apply it to a wall at home, the final appearance may be very different depending on the outdoor light, or artificial illumination in our room (Figure 1.5). The following image shows a simultaneous colour viewer (http://www.gtilite.com/products/scv-simultaneous-color-viewer), which demonstrates the different light sources: lighting in the home (such as tungsten, which is a warm white light), fluorescent lighting commonly found in offices and commercial environments, and average outdoor light (https://www.gtilite.com/pdf/Various-Light-Sources.pdf).

Choosing colour can be an expensive process for consumers, and marketing paint to a DIY market is fundamental for maintaining consumer loyalty. As exampled in a rebranding exercise by a UK household paint manufacturer (1998), the aim was to understand the change in the domestic paint market. Their key insight into its consumers' choices was that they did not want *paint* - they wanted help with matching colours. Based on the possibility of living in a painted room that may be hideous, often led to a 'non-purchase, delayed purchase or compromise. People needed help – colour help.' The slogan for the manufacturer's paint-matching advertisement was, 'You find the colour, we'll match it' (https://www.marketingsociety.com/the-library/2008-dulux-marketing-communications-case-study). This advertising campaign made a significant visual impact on British DIY consumers.

When presented with an array of colour swatches, it is surprising we can still be uncertain about making colour matches. In general, humans are fairly good at colour constancy (McCann and Rizzi, 2011). We are able to discount misleading information, such as modulations in colour caused by surface texture or effects (weave, bumpiness, grain), highlights and shadows. A brick wall that is painted white is still perceived to be white even if it is a bright day or a dull day. As demonstrated in Figure 1.6, although the pink jacket demonstrates a wide range of reflectances, highlights and shadows, we still perceive the colour to be pink.

Figure 1.5 Illustrating the appearance of the same colour under different illumination. Simultaneous Color Viewer (SCV) produced by GTI Graphic Technology Inc.

Figure 1.6 Dulux advertising campaign 2008 (courtesy: AkzoNobel) (http://www.mischiefpr.com).

However, comparing the appearance of the clothes and the colour swatches of the advertising campaign (Figure 1.6), there is a difference between flat surfaces, textured materials, and materials, each demonstrating complex angles of reflection. Furthermore, as shown in Figure 1.7, although the coloured square is seemingly flat under direct light, by changing the angle of the illumination we perceive a range of bumps and textures; the coloured square is transformed into a noisy surface of highlights and shadows.

Therefore, in order to obtain an exact colour match from a textured material, by simply measuring a surface using a colour measuring device, such as a spectrophotometer, could lead to a range of results. By moving the spectrophotometer across different areas may lead to a variety of colours or tones, which may result in an unwanted colour reproduction and a potential DIY blunder (Figure 1.7, right).

In order to model the appearance of complex surfaces and geometries, scientists and technologists are now striving to find methods that accurately capture and measure low relief, texture, and surface qualities that incorporate quantitative and qualitative methods. The objective evaluation allows a quantitative validation of data acquisition methods and measurements of the real world. It provides information about the feasibility of reproducing details, colours and textures. On the other hand, the subjective evaluation provides a sense about whether a reproduction is pleasing or appealing.

We make use of different methods and techniques to judge the quality of 2D rendering systems such as printers, cameras and screens, but little work has been undertaken in the assessment of 3D reproductions (as described in Chapter 2). Not only the extension of 2D quality metrics appear to be the answer but also previous methods from the field of optics are just as suitable to estimate quality. The current lack of standardised methods in the 3D print industry can be compared to the colour printing industry of the 1980s. Instead of working towards a common standard to unify results and open the discussion about quality. each emerging 2D industries were developing their own file formats, hardware systems and workflow parameters.

It seems that no matter how accurately we can measure the properties of colour and textures, from the point of view of perception, the human visual system is adept at interpreting these two-dimensional visual clues to imagine three-dimensional spaces. The human visual system is also highly objective and critical in identifying when objects and spaces do not appear to be correct. Therefore, subjective and objective approaches are essential for comparison and improvement to evaluate the quality of the outputs.

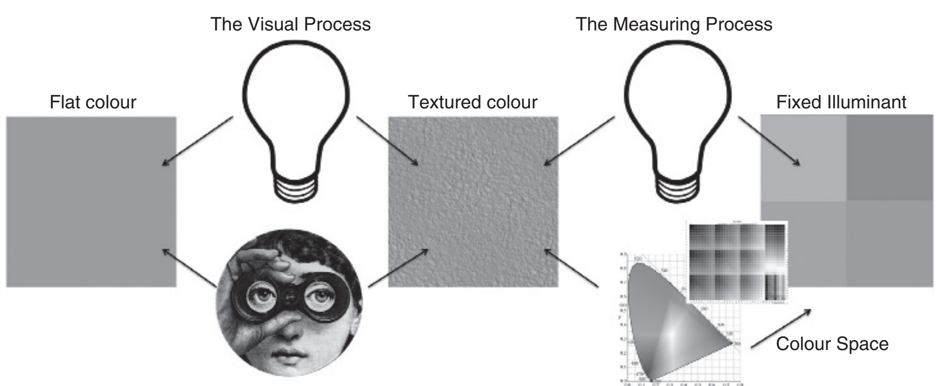
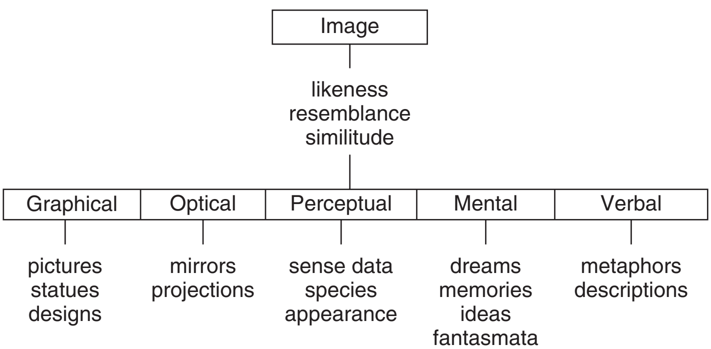


Figure 1.7 Human perception is able to discriminate an overall colour and discount texture (left). Measurement of the surface could lead to an unwanted reproduction of colour (right).

1.3 Images, Pictures and Reproductions

What is it about an image that is so compelling? And what is the relationship of an image to its reproduction, representation on screen or on paper? Or even a reproduction of a reproduction? Images in the twenty-first century are ubiquitous. Alongside our own old photos kept in shoeboxes or on hard-drives, there is the World-Wide-Web, with unlimited access to digital databases, *Picassa* and *Flickr*, commercial stock-imagery, as well as magazines, books, museums, galleries and archives, we are surrounded by pictures and images. A quick word search for 'image' on the Internet reveals about ten billion hits. Yet, as regularly demonstrated in news reports, images can still cause offence, are feared and venerated, and can even bring about violence and death. Images could be considered as wide ranging including something that is fixed to the more ephemeral and fleeting, including paintings, pictures, diagrams, graphs, illusions, photos, cartoons, ideas, memories, dreams, imagination, or our mind's eye. Images are 'notoriously ambiguous' (Mitchell, 2006), we rely on different images to distil complex information (info-graphics, pie-charts, bar-charts), provide accurate and specific information (city maps, sea charts, architects plans, car-repair manuals) or to tell a story (sketches, paintings, films). Each of these carries specific codes for interpreting or reading. A misinterpretation of a map or a road sign may even be life threatening. The following arrangement, by cultural thinker W.J.T. Mitchell, suggests how some images can be categorised according to different disciplines based on how we might use them, including arts, optics, perception and psychology (Mitchell, 1986).



The most common way of looking at images is via photographs, on screen or as prints. Our ongoing fascination with the camera, is the ability to extend beyond the human eye. Likewise, spectacles, magnifying glasses, telescopes and microscopes are an aid to vision, which can change the scale of objects, bring objects closer and draw the viewer to things, surfaces or materials, and may assist in our understanding (Edwards, 2006). This idea is certainly not new. In the eighteenth century, a short story entitled *Micromégas* (1752) by Voltaire (François-Marie Arouet 1694–1778), describes Micromégas and his travelling companion who had evolved on different planets; both are giants by Earth's standards. As part of their quest to find new insights and different life forms, they have arrived on Earth, but because of their huge size are unable to see the human inhabitants. They assume that as they cannot see any signs of life, the planet Earth must be uninhabited. Micromégas' companion, who is from Saturn, by chance spots a speck swimming in the sea, and realises the life form is communicating. However, they conclude that because these life forms are so small, their brains must be incapable of holding reasonable thought, and therefore must be stupid. The story of Micromégas demonstrates that although our vision of the world seems effortless, there is a difference between looking, seeing and apprehending; thus, from an epistemological perspective, we ourselves define the limits of our knowledge. Likewise, the story demonstrates limits in technology; as we are able to see clearly or closely, we are able to gain new insights about the everyday things around us. Today, we have powerful methods of capturing the unseen and, furthermore, if extended to high-speed motion capture, high definition, X-ray, infrared or microcameras, then our ability to see beyond human vision creates new insights and challenges our own assumptions of our world. Traditional photography captures different intensities of light through the physical changes as a chemical reaction, or chemical solutions using light-sensitive chemicals. Digital image sensors capture the brightness of light, that in turn are converted into electrical signals and converted into a numerical code. Likewise, the mechanism for translating images into a code for the brain, visual information, is converted as neural impulses to the brain whereby the brain creates 'symbolic descriptions' that have no relationship to images or pictures but generate their 'own alphabet of nerve impulses' (Ramachandran, 2012, p. 47).

We continue to be fascinated by images. The photographic recording, such as the Hubble Telescope, has bought the furthest regions of our universe closer to us, and in turn, the process of looking at the world through a lens, such as photography, has become a medium that anchors us to our world. However, the downside is that we use the camera to mediate our experiences without properly looking, which can result in a secondhand experience. The image is not an image at all but a direct re-presentation of lived reality (Edwards, 2006, p. 69). Art historian James Elkins echoes Voltaire's message in his book *How to Use Your Eyes* (Elkins, 2000), who suggests that looking is based on memory, previous experience and day-to-day routine through familiar landscapes; we are not actually seeing but perceiving what we think it should look like. If we 'see' every detail it would be an exhausting experience. Elkins describes how familiar everyday things slip by unnoticed. He reintroduces the reader to a range of commonplace objects, including postage stamps, moth wings, sand, rainbows, and *Craquelure*. *Craquelure* are the tiny cracks that appear in the surface of paintings. These cracks and the formation of patterns can tell us about its provenance, how it was painted, varnished or repainted, conserved or even ill-treated.

The camera has changed these perceptions and impacted the way we look at things, 'Strange realism of the camera … is a compelling illusion' (Edwards, 2006, p. 2006, p. 69). The camera can reproduce pictures and via imaging software and the Internet, we can modify them -to any size, send files anywhere, and reproduce images for any purpose. The same image can be viewed on millions of different screens, accessed from thousands of different locations and surrounded by many different contexts. Originally a painting, such as *The Annunciation Diptych*, a small devotional piece by Jan van Eyck (1390–1441) (https://www.museothyssen.org/en/collection/artists/eyck-jan-van/annunciation-diptych), may have originally resided in a private house or chapel. The Assyrian carved panel (Chapter 2, Figure 2.5) was once part of the architecture in an ancient building. However, the meaning of the artwork no longer resides in the place where it was painted or installed.

According to English writer and painter John Berger (Berger, 1972), looking at and interpreting artworks, and the process of translating real life into artworks, is less spontaneous and natural than we assume, and is more to do with training, habit and convention. For example, the use of perspective is unique to European art, which focuses objects towards the gaze-appearances travel in and the lines of perspective tend to draw the eye to the centre of the picture, but as we walk about or travel, our perception travels with us. The photograph can do this perfectly: one can point a camera down a street lined with buildings and the camera produces a picture in perspective.

French philosopher and art historian Georges Didi-Huberman (B.1953) suggests our perception of an artwork may be changed as we move closer to a painting and celebrate its wonder. His suggestion is to not look at a painting but to see it. By getting closer we can analyse all the detail and arrive with an exhaustive description, we can see the brush marks, the defects, and the embedded brush hair. Under close scrutiny, we can find and describe all the microelements, but from a distance we understand its drama (Didi-Huberman, 2004, p. 229). A good example of this can be found in the paintings by Diego Velázquez (1599–1660), who was a master of different contrasts and textures. His work is intriguing:

when viewed at a distance the canvases present an opulent and detailed rendering of precious pearls, lace, metal, fur and feathers, and gold, silver metal work, and glittering brocade – all rendered in a seemingly high contrast and dynamic range. At a distance, these constructed compositions are a mimesis of materials, but close up, the micro details appear out of focus and gestural (Chapter 2, Figure 2.33). Velázquez celebrates his still-life subjects as a careful study of appearance through the rendering of paint - by bringing together his knowledge of materials, he is exploiting our assumptions that drive perception (Ramachandran 2012, p.51).

With the invention of photography and film, comparisons can be drawn to the early twentieth century, when artists began to capture the world mediated by the lens. These ideas eventually led to a logical progression of the moving image or cinema – a twentieth century synthesis of art and science. Photographers such as Eadweard James Muybridge (1830–1904) was able to capture the movement of animals and humans using trip wires and a row of cameras (http://100photos.time.com/photos/eadweard-muybridge-horse-in-motion), and Étienne-Jules Marey (1830–1904) invented a hand-held rotating drum that could expose 48 plates in 72 seconds (https://www.youtube.com/watch?v=dU5llQM7lzs). Composition and movement are some of the aspects that provide more dimensions to a flat media and connect painting, film and photography. This photographic idea of movement was also captured in the painting. The Fourth Estate (1901), by Giuseppe Pellizza da Volpedo (1868–1907); by playing with transparencies and changes in light, the artist creates the impression of movement among a compact group of people (http://museodelnovecento.org/index.php/en/collection?giuseppe-pellizza-da-volpedo). This is similar to the work by Gaetano Previati (1852–1920), *Funeral of a Virgin* (1895), in which we have the sense that the crowd is moving so lightly as if they were ghosts (http://pinacotecabrera.org/en/collezione-online/opere/funerale-di-una-vergine).

1.3.1 The Anxiety of the Reproduction

Perceptually we know that images – paintings, prints, photographs – are visual statements, that by their flatness, are illusions of our world. We are experts in looking through or into a flat-land and understanding its spatial dimension. As exampled by the marble *Veiled Virgin* (Figure 1.2), these images and objects, and the stuff from which they are created, resonate on so many different emotional levels.

Cultural theorist of the early twentieth century, Walter Benjamin (1892–1940), stated in 1936 that an original image cannot exist without the knowledge of a reproduction. However, in the twenty-first century, as more images are viewed on screen, the aura of originality in the age of mechanical and screen reproduction is so far removed from its place of origin that even reproductions are now commonplace (Benjamin, 1936). To source an image in the twenty-first century, the art historian, curator, publisher, researcher or art lover has many opportunities to search for images. Although we have access to more coloured images, the issue of image quality on the Internet is questionable. Of course, the accuracy of printed colour reproduction has improved over the last hundred years, but a badly reproduced colour image might be considered too misleading, and a black and white image tonal image a more useful alternative. Can we rely on the Internet? As an example, the thumbnail images collected from a Google image search of a famous painting demonstrates the many variations of colour gamut and contrast (Figure 1.8).

The work by Doug Manchee, *20 Works of Art in the Age of Mechanical Reproduction* (2006), dramatises the variability of images we think of as reproductions. Manchee gathered reproductions of well-known artworks from books that were printed at different resolutions, sizes and colours, and which were often cropped to fit to the book format. Manchee scanned and superimposed them, resizing to align the primary elements of the composition. In the final composite image, he reveals all the layers. Here one can identify the different halftone processes, different colour gamuts, cropping and stretching, as well as realising that compositions are fitted to suit the demands and shortfalls of the publisher, rather than keeping the integrity of the image.

Moreover, looking at the range of colours in the screen grab (Figure 1.8), one could ask which is the closest to the original? This poses a problem for gallery curators wishing to maintain control over the works in their care, and, furthermore, in the current interest in the creation of textured paintings that

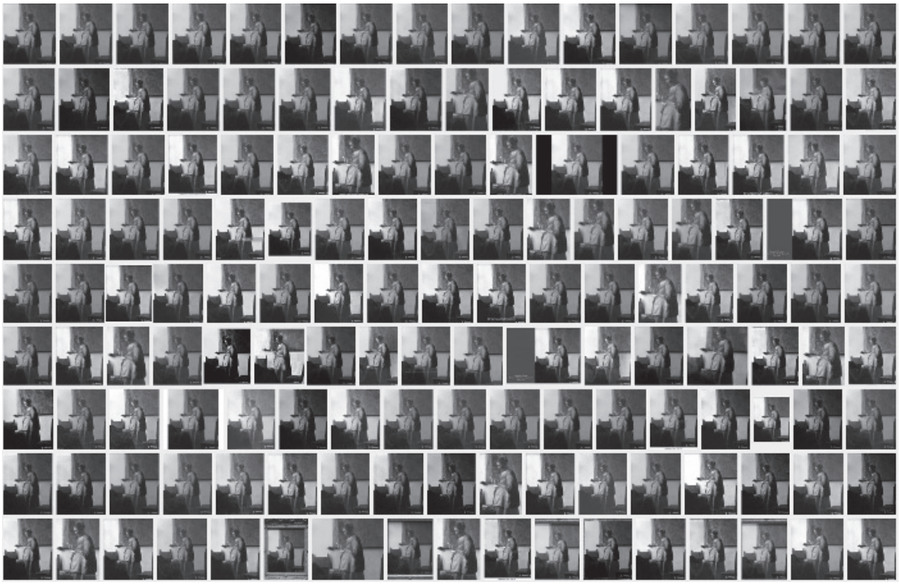


Figure 1.8 A screen-grab of a page of thumbnail images from an image search of Johannes Vermeer's *Woman in Blue Reading* (1664).

demonstrate brush strokes, does this add yet another dimension of complexity? What of the term original reproduction – an oxymoron?

1.3.2 Reproducing Images: Tools of the Trade

From the sixteenth century onwards, etching and engravings of paintings and drawings were highly sought after and prized in the print markets. A large number of chiaroscuro woodblock prints made in the mid-sixteenth century were designed solely for a print market. Prints were an important source of artistic production in circulating and expanding awareness of the original paintings, and through reproduction to generate income from an original painting. Often these prints were the primary source of access for the public and scholar; therefore, the reproduction needed to be accurate. The translation of brush strokes to printed marks, colour to tone, required skill and knowledge, and the transcription from a painting had to be undertaken in reverse on the plate. Our contemporary understanding of original and editioned prints (the artificial method of limiting the quantity of prints that are numbered sequentially) was less of a consideration, and blocks were printed in different colourways and often modified and reworked. The art works by Albrecht Dürer (1471–1528), made in the sixteenth century, were prized and highly valued, and remain so today. It is also highly unlikely that Dürer made his own prints; instead a studio comprising different skilled artists would have transcribed his drawings into line on to woodblocks, which were then carved and printed as a relief. Likewise, John Constable (1776–1837), who was painting gestural and highly evocative landscapes at the turn of the nineteenth century, also attempted to capitalise from the burgeoning print market and to commercially reproduce his paintings. David Lucas (1802–1881), working with the medium of mezzotint, used a burin to transcribe the painterly marks of Constable's brush strokes on to copper. Working from black to white, the fine process of mezzotint enabled the engraver to convert colour and texture into a full range of marks and tones. (see Case Study 13: Analogue Printing Methods). Lucas' skill could be considered as an equivalent to the photographer's approach to sharpening, dodging and burning, deepening the shadows in some sections and increasing the contrast in others (Wax, 1990, pp.120–122).

Speculation on whether optical devices were used by Old Master painters to accurately draw scenes and portraits has undergone considerable (and often heated) debate over the last few years. It seems that historians, scientists and artists are both passionate and divided about how artists make art: at worst regarded as cheats, who employ clever trickery using lenses and drawing machines, or at best, artists able to transcend any technology whereby artworks are solely achieved by eye and hand. Martin Kemp, writing on the history of the art and sciences, documented a significant body of apparatus that could assist the artist, including the drawing devices by Leonardo da Vinci (1452–1519), and perspective machines by Leon Battista Alberti (1404–1472). As recorded in *De Pictura* in the sixteenth century, Alberti describes how the camera obscura and drawing frames were important components for arranging and composing figures and objects. Likewise, in terms of describing the influence of illumination, colour and composition, and careful lighting, composition in their paintings, Kemp compares the contemporary photographer to Vermeer. Kemp explains that Johannes Vermeer (1632–1675) was not making a 'mindless or mechanical image' but the artist was making 'aesthetic choices at every stage', and 'like great photographs, can be regarded as utilising optical mechanics for highly individual effects' (Kemp, 1990, p. 195). Furthermore, Kemp's observations call to mind the work of artist David Hockney (1937–), who during his career has explored many different imaging-making technologies – contemporary to their time – including Polaroid cameras, fax machines, iPads (as sketch books) and digital camera-recorders.

Hockney is continually interested in the different ways to capture and record the landscape, using a range of media and technologies in a highly individual way. Hockney's own work and ideas originate in drawing and therefore he is expertly able to recognise drawing traits and characteristics by other artists who sketch and draw. It is possible that as Hockney was more responsive to technologies as used by Old Masters, this may therefore have triggered a recognition in marks made in a sketch by nineteenth century painter Jean-Auguste Dominique Ingres (1780–1867), and to view it with fresh insights and understanding. He compared the drawing marks made by Ingres to a drawing made in 1975 by Andy Warhol (1928–1987) who often used a camera obscura to project an image in order to trace its outline. This observation led to a lengthy investigation into drawing methods and apparatus. His suggestion that Old Masters used drawing machines resulted in a publication, *Secret Knowledge* (2001). The story behind artist David Hockney and experimental physicist Charles M. Falco's investigation into how artists used mechanical devices is described by Lawrence Weschler in his blog, *Through the Looking Glass, Further Adventures in Opticality with David Hockney* (http://www.believermag.com/hockney/lookingglass). Weschler explains that although not based on any hard science or fact, Hockney had collected photocopies of artworks and had pinned them across a wall, asking: 'When did an optical look first emerge?' Hockney's suggestion was that artists were not necessarily cheating, or that all Old Masters were using optical devices to make their art, but analogous to the twentieth century influence of photography, billboards of the 1970s, high dynamic range imaging of the twenty-first century, or objects rendered using CGI, we begin to recognise characteristics or trends in the way pictures appear to us. Artists may be influenced by a particular characteristic when creating images, and likewise may be drawn to a particular method; for example, artists working on computer drawing tablets may modify their methods simply by the constraints of the pen and the tablet or the software they are using. One can quickly recognise how images are filtered or the software that has been used to create a particular style or manner, for example, the depth of field as viewed through a camera obscura, or the tonal range as viewed through a *Claude Lens*, or an image that is filtered in Photoshop. As Elkins suggests, our unconsciousness is persuaded and mediated by the things that surround us.

From artistic to commercial exploitation and mechanisation, drawing devices demonstrate a bridge between reproduction by hand, to reproduction by photochemical, and then photomechanical means. In the eighteenth century, the silhouette apparatus enabled an artist to create profile portraits. The sitter was illuminated by a spotlight, and paper placed behind them. The artist could then draw around the shadow. In 1786, the French musician Gilles-Louis Chrétien (1754–1811) introduced the *Physionotrace* machine, and up to twelve images could be produced at the same time using an engraving needle. Similar to a *Pantograph*, images could also be created to a different scale. The Pantograph was used widely as an engraving tool for engraving into metal (Case Study 4: Coins and Medals). The English potter and manufacturer Josiah Wedgewood (1730–1795) was able to create silhouettes of his sitters using chemical methods (although unable to make the images permanent), by painting the background surface with light-sensitive chemicals and illuminating the sitter against the light-sensitive background. In the early nineteenth century, inventor Charles Babbage (1791–1871) described two other drawing machines called the *Prosopographus* and the *Corinthian Maid*. By means of a Pantograph and Camera Lucida he captured the likeness of the sitter.

Early photographers attempting to capture scenes on to paper using silver chloride were frustrated by the fugitive nature of these images. Other experiments conducted by William Henry Fox Talbot (1800–1877) and Alphonse Poitevin (1819–1882) worked with pigments and presses to make their images more permanent. Realising the fugitive nature of photography, and to obtain a light-fast image, printers sought to experiment with pigments instead of dyes, and with plates and presses instead of sensitised paper. Printers found that by combining print and photography they could not only produce an image that would last much longer, but the image could also be reproduced many times and at greater speed. Printers at the end of the nineteenth century were able to reveal an astonishing range of pigment and carbon processes. The most reliable, and possibly the most beautiful, was the Collotype (Thirkell, 2000) and Woodburytype (Atkinson, 2005; McCallion, 2017), novel processes that used the light-sensitive qualities of bichromated gelatine to convey detailed and subtle continuous tones.

Since the fifteenth century, the colour print has evolved through an incremental process of comparison and commercial expediency (Gascoigne, 1997; Benson, 2008). Printing has progressed through the development of techniques that emulate processes, which were perhaps too laborious and time consuming, through halftoning and colour, the objective was to provide a near facsimile of the previous technology, but remained appealing and captured the elements of the process it was emulating. This can be demonstrated, for example, in the use of the mezzotint to emulate the colours and brush marks of a painting, lithography to emulate the marks of a woodcut or a photogravure to emulate the qualities of a photograph. One could suggest that the attainment of such qualities through mechanical methods could be considered to be a compromise of quantity, and speed over quality.

In 1881, a commercial method for printing an image using three colours was made possible by Frederick E. Ives (1856–1937), which he later refined in 1885 using a halftone screen. His technique employed the same principle as James Clerk Maxwell's (1831–1879) theory, of exposing an image through three coloured filters. Working from Fox Talbot's photogravure process, Ives developed a method for breaking down an image into small dots, but Ives used a more symmetrical matrix. He made a series of ruled opaque lines on to glass, each line of the same equal width, which was then placed on top of a second ruled glass screen and positioned at right angles, to give a pattern consisting of small openings on an opaque background. This method of halftoning – the process of translating an image into a series of graduated dots – has provided the basis for the way we give thought to images and, akin to Hockney's search for the 'optical look', the halftone such as *Benday Dots*, *Letratone*, stochastic screens, the halftone pattern may be considered as the optical look of the twentieth century. In the latter half of the twentieth century, printed colour has been further advanced by electrostatic print, enabling colour, text and image to be printed in one pass. As the refinement process of inkjet has attained higher levels of accuracy, a range of processes are able to emulate all the marks, colours and qualities of both photographic and traditional printer techniques; it has widened the scope for artists to engage with a new medium.

The next steps in the twenty-first century are the technological developments in colour and inkjet printing, for example, inks that can be physically deposited to create optical nanostructures (Yakovlev *et al.*, 2016) or printing organic thin-film transistors (OTFTs) that will play an important role in electronic devices, for example, e-paper, antennas, sensors, batteries and solar cells.

1.3.3 Reproducing Images: Colour and Texture

In this fast-moving industry, commercial and industrial manufacturers, makers of hardware and software require cross-platform standards and benchmarks. In order to bridge how images are reproduced, we need to understand how different surfaces can be captured, measured and reproduced. There are many potential different industrial and commercial uses and applications. The print industry is beginning to incorporate novel materials, decorative printing inks, textures and embellishments to enhance the surface qualities of packaging and prints. Printed textures are considered acceptable where the surface is purely decorative (i.e. repeat patterns for wallpaper). For some applications a low-relief texture is applied to photographic images, however a correlation between image and a convincing naturalistic rendering of texture has proven to be difficult. A well-used traditional CNC method to create a photographic relief is to assign a range of heights according to the tonal range of the image. This works well for greyscale but works less well as a coloured image. The conflict between texture and image is more apparent where there are contrasts, edge contours or attempts are made to distinguish relief from a flat picture plane. The appearance of false shadows and edges tends to amplify these problems.

As humans we inherently know what appears to be wrong, whereas computers have no such powers of perception. As demonstrated by halftoning, an image is converted into dots and the process of printing a full colour image is achieved by making a colour separation of each colour channel, after which each channel is converted into a greyscale image. When reprinted, using the four-colour process, colours will optically mix to appear as a full colour image (Burch and Gamble, 1983). On inspection of a print under magnification the dots are still discernable but at an appropriate viewing distance we perceive a continuous tone image. In comparison to an image that is printed, for example, by photocopier, inkjet or offset lithography, the clustering of the halftone dots will appear to be very different, often resulting in very different reproductions. To create a halftone reproduction of a textured surface, texture is implied by shadow and highlights, which is converted to dense areas of dots to create shadows, and absence of dots to create highlights. To obtain a similar colour and tonal range in traditional painting there are different methods to use; for example, Rembrandt used many layers of thin translucent glaze to create a deep black while Jan van Eyck applied thick dashes of white to indicate a highlight. Figure 1.9 illustrates the difference between a brush stroke, the density of a colour that can be obtained by overloading paint, the appearance of a brush stroke under magnification and a brush stroke that has been electrostatically printed and then captured under the same magnification.

1.3.4 Reproductions versus Forgeries versus Copies

In Dafen Oil Painting Village (http://www.dafenvillageonline.com) in the suburb of Shenzhen in Guangdong province China, an army of artists produce paintings and drawings on a mass scale. Highly skilled artists copy from Old Masters to produce artworks that may either resemble an image originally painted by Picasso, Manet or Van Gogh, or may be commissioned to incorporate unusual subject matter and incorporating painterly styles, such as a portrait of the customer or a picture of their wedding or favourite pet. Arranged along the walls of a nearby seventeeth century country mansion house, serving now as a function hall for weddings and conferences, are arranged Old Master oil paintings in ornate gilt frames. On further inspection these paintings are simply inkjet reproductions on to canvas, upon which brush strokes of varnish have been added by hand to obtain a surface texture. However, to the persistent eye, the brush strokes do not necessarily relate to the edges or sections of paint, but strokes are applied randomly.

How are these two examples connected? They are linked by our preoccupation with reproductions and artworks, the use of texture that shifts from what are ostensibly copies to convey something else – a facsimile that enhances an existing collection, a pseudo relic of the past, a long-forgotten treasure or to simply to surround ourselves with materials that move beyond the flat poster. Curiously, one of the paintings in the Ashton Court Mansion House is a copy of the *Portrait of Sir Thomas Gresham*; the real

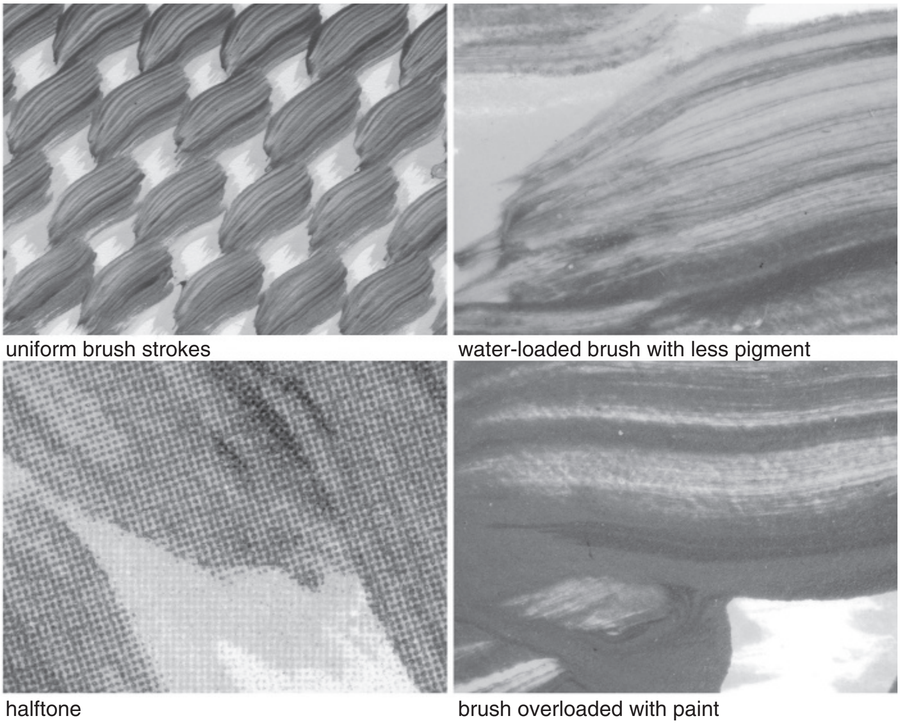


Figure 1.9 Darker brush strokes over lighter coloured uniform brush strokes, a water-loaded brush with less pigment, brush overloaded with paint, halftone at 40× magnification.

painting is exhibited in the Rijksmuseum and discussed in Chapter 2 (see Figure 2.30, Anthonis Mor (1517–1576), *Portrait of Sir Thomas Gresham*). Moreover, analgous to the artists working in Dafen Village, Figure 1.10 is a reproduction from a copy of the original painting. This reduced print version has lost much of the fine detail and mid-tones, and has more than likely faded, hence giving a greenish skin tone to Gresham's hands and face.

We are now highly accustomed to viewing works of art on screens, as postcards and printed reproductions. An established market for many museums and art galleries is the 2D print-on-demand fine art poster, enabling visitors to request any painting from collections that can then be printed at different sizes on different papers or canvas, one can even browse entire collections online without putting a foot inside a museum.

There is also a commercial initiative by museums to accurately reproduce paintings with colour and surface texture of brush marks (https://www.metmuseum.org/blogs/digital-underground/posts/2013/3d-printing). Museums have used high-tech scanning methods to minutely capture the *x-y-z* data of the surface (as described in Chapter 3, scanning methods to accurately capture the data and materials and methods to print them). When scanning paintings for conservation purposes, what then can be done with all the data? There remains a fundamental difference between paintings made by artists and a digital relief printer. In current digital relief printing a topographical height map – similar to the contours one would see on a map – a digital printer applies texture and then a layer of CMYK colour is added. The painter applies colours that are bound in mediums and materials to create texture, adds different directions to strokes, and layers of colour where needed. The aim of the artist is to strategically place brush strokes that direct the viewer's focus on particular objects or to generate an energy through the application and overlayering of marks, by orientating the brush marks in different directions to create perception of depth or specific regions.

Figure 1.10 A copy of a painting of *Portrait of Sir Thomas Gresham* in Ashton Court Mansion House, Bristol. The original is in the Rijksmuseum, Amsterdam.

There is of course a difference between forgeries, copies and reproductions. Forgeries are made to mislead or dupe buyers into believing they have purchased an artwork of value. The move from poster art and inkjet to more textured artworks may provide the consumer with a facsimile as close as possible to the original, which may even provide insights to the magic or aura of authenticity. The painted works produced in Dafen Village, although more than likely executed by a highly skilled painter, do not purport to be originals but are works that imitate a painterly style. It is interesting to note that copying, capturing and even studying the ways fakes and forgeries are made may provide insights into how painters paint, for example, how images are composed, the range of brushes and drawing tools that are needed to create different marks, and which may also provide insights as to whether a painting is authentic.

1.3.5 Are Facsimiles and Replicas Important?

Whether one considers copies and reproductions from a painting as art, fake or forgery depends on the intention of the maker, seller, dealer and collector. Are computer-generated brushstrokes from a digital scan or artists working at Dafen Painting Village realistic or more convincing than each other? These artworks sit in an uncertain position in the commercial art world: Are they art? Experiment? Entertainment? Do they hold any value? They are not unique and so what is their place to a museum or a collector? Today most consumers are eager for things and experiences that are authentic.

Museums have undergone a radical change since the 1970s, incorporating stunning new spaces by building in to traditional buildings or the creation of brand new buildings. In this climate of 'new museology' and through increasing social change and education, these are no longer just places for the elite, but museums are increasingly about openness and social inclusion that appeals across disciplines. Although museums are still in charge of caring and preserving a nation's cultural heritage, this new openness has enabled the curator to organise and present their cultural artefacts in new ways, by the 'breaking down of established boundaries … to some transgressing of the boundaries of specific subject disciplines' (Ross, 2004, p. 96).

Technology provides us with new insights as to how a painting or an artefact is made. 3D scans and computer-aided methods provide us with new methods to recreate them. They can also be used to improve our experience of exhibitions on multiple levels – popular/scholarly, aesthetic/critical – and also to be able to contextualise painting and artefacts in a new light (Freedberg, Jackson-Stops and Speer, 1987). Museums also incorporate facsimiles of artefacts by assisting the curator in completing their display or to create a narrative for existing objects. It is unlikely that the majority of the public are even aware that some artefacts are replicas, as it is in the skill of the artist to create realistic matches to existing sculptures and coins. Possibly the most well-known and iconic facsimile is the replica of the *Rosetta Stone*, which is in the Kings Gallery, British Museum, London. The original stone is just a few rooms away. George III officially donated the stone to the British Museum in 1802. Even in the 1800s, the preservation of the stone had always been a concern, and so it was placed behind glass. However, after complaints from visitors who wanted to touch this iconic stone, a compromise was found and a replica made, which is now in the Kings Gallery. Indeed, this replica has assumed its own significance, history or aura, and during its many years as a facsimile, has required regular attention and maintenance. It is interesting to note that even though it clearly states it is a replica, visitors still wish to photograph and touch it.

In the late 1980s, author and playwright Alan Bennett created a fictional conversation between two real-life characters – Queen Elizabeth II and Sir Anthony Blunt. In real life, Blunt was the Surveyor of the Queen's pictures, but was later exposed as a Soviet spy and stripped of his knighthood. The scene takes place in the Royal Picture Gallery in London, during which they discuss their fascination for forgeries. The Queen asks Blunt why the Vermeer paintings by Han van Meegeren, painted in the 1940s, were not exposed at that time as forgeries. It seemed inconceivable to the Queen character that these 'terrible daubes' were anything but fake. However, the Blunt character suggested that even the most brilliant forgery of their time, even though vetted by experts, they would eventually 'come to be seen as old fashioned'. Hundreds of works had been forged by van Meegeren and had been authenticated by important historians and critics of the time and caused a great deal of embarrassment and paranoia regarding forgeries. Alan Bennett was referring to the Dutch forger Han van Meegeren (1889–1947), who was able to imitate the works of the Old Masters including Frans Hals and Pieter de Hooch, earning him the equivalent of tens of millions of pounds (in today's money). He also claimed to be the forger of a piece initially authenticated to be a piece of work by Vermeer *The Supper at Emmaus* (1937), which had originally passed hands from van Meegeren via a Nazi banker and art dealer to Hermann Göring, and was finally discovered along with thousands of other looted works. Yet, as highlighted by the characters in Bennett's play, 'it is inconceivable to think it is not what it claims to be'. Artworks that are so readily thought to be the real thing in one time and context, that based on new knowledge gained through new technologies, can impact our perception as to how artworks appear today (Morris, 2009). These comments, although fictional, could be compared to Hockney and Elkin's observations that on seeing old artworks from a fresh perspective, as if for the first time new insights would be revealed.

In the UK, Tom Keating was regarded as an renowned forger of the twentieth century. Keating, who was also an art restorer, would have gained insights into how painters created their works and appropriated their methods to make new or minor art works and through the late 1950s and 1960s, placed his forgeries in auctions in the UK and with London dealers. He is reported to have forged over two-thousand paintings by around hundred major artists. An interesting addition to Keating's forgeries was his inclusion of an invisible signpost in his pictures. He started by daubing rude comments in lead white on the canvas before he started the painting, knowing that if the work was X-rayed, the lead white would appear. In 1987, John Drewe, responding to a small advert in the *Private Eye* magazine in 1987, conceived a plan to defraud the artworld with artist John Mayatt, who could turn his hand to painting many styles of nineteenth and twentieth century painters. Described as the 'the biggest art fraud of the twentieth century' by Scotland Yard in London, Drew and Mayatt created and sold around two-hundred forgeries through private dealers and auction houses (Battersby, 2014). Described as the 'one man Renaissance', Shaun Greenhalgh was jailed in 2007 and made hundreds of forgeries, including, paintings, ceramics and metalwork (Greenhalgh, 2015). He explained that he always put a 'tell' into the works, so that to a trained eye, would show they were not real. The work *La Bella Principessa* was attributed to be by Leonardo da Vinci, but has also been claimed by Greenhalgh to be his own work. The *Bella Principessa* is a portrait of a young woman in profile wearing a fifteenth century style dress. Greenhalgh claims the portrait was drawn by him in 1978 of a young woman called Sally, whom he had met in Bolton in 1975 (Jones, 2015). The provenance of the work remains contested.

One may wonder how many works are in museums and private collections that have passed as real. The long-running BBC programme entitled *Fake or Fortune* considered the science behind Old Master paintings. Using multispectral scanning or X-ray may reveal hidden clues and hidden information about a work. According to the BBC there are over 17 500 'unattributed' oil paintings – or by an 'unknown' artist – in UK public art collections. A *sleeper* is a term commonly used by art experts to describe a painting that has been miscatalogued or just overlooked, in a large collection (http://www.bbc.co.uk/programmes/b01mxxz6).

Fakes and forgeries remain in the public consciousness as works made by a roguish miscreant who steals from the rich and hoodwinks the experts, who dabbling in forgeries and, having served their time, are then invited on television programmes to reveal their secrets. The flip side is the impact on those who purchase forgeries, those who assumed they had purchased an investment only to find their purchase seized and destroyed thus losing thousands or millions when it was found to be a fake. The difference here is the relationship of art as a commodity that is bought and sold through dealers and auction houses or art that is enjoyed for the sake of its pictorial qualities that may be a copy or a reproduction.

Of course, throughout history there have been countless small workshops and large factories intent on profiting from any number of consumable articles, intent on the production of fakes and forgeries, including drugs, banknotes, handbags and artworks. In particular, inkjet printed artworks present a new opportunity for the forger. In order to address issues relating to reproduction of digital prints, one approach has been to tag artworks, whereby each print is allocated its own security code and DNA, which can then be linked to a certificate of authentication. In order to prevent attempts to copy the tagging many layers of complexity are added to the tag (www.tagsmart.com).

1.3.6 Copying from Old Masters

According to Josh Kaufman it only takes twenty hours to learn a new skill (Kaufman, 2013). Experts in a particular field may well disagree; asserting it takes a lifetime. However twenty hours may be enough to give the learner an idea about the complexities of the skill. Analogous to the way a mimic chooses to portray a famous character, they may only need a recoginsable attribute, for example, their voice, a gesture, or their posture. Today there is less access to learning from so-called Old Masters, but teaching is replaced with a myriad of how-to books and online teaching or just by searching YouTube. Likewise, we now have the opportunity to gain insights into how artists use different tools to create images, and how artists observe and reproduce different textures in paintings, prints and drawings. Secondly, we can also gain an understanding of artworks made by forgers and copyists, as they have studied brushstrokes and signature styles of the Old Masters. The objective for our study, is to gain an understanding of how forgers and copyists set about capturing the qualities that are important for a convincing likeness.

Copying from Old Masters was traditionally a well-established method for training the classical student and a direct way to learn the techniques of painting and drawing, understanding of tone, perspective and anatomy. Students began by observing and copying directly from their master, or as an alternative teaching aid by drawing from plaster casts of classical sculptures. Students in the Academies were only allowed access to life models once they could demonstrate proficiency in drawing from casts (http://www.ashmolean.org/departments/castgallery/about). Leonardo da Vinci, who had trained in the workshop of Andrea del Verrocchio (1435–1488) in Florence, learnt by observing and copying the work of his master. According to Vasari, Leonardo had painted one of the two angels in Verocchio's *Baptism of Christ* (1475). Verocchio was so overcome by da Vinci's painting that he declared he need never paint again. Following the same teaching style, similar evidence shows students' attempts in copying the work of Leonardo. A stunning example recently revealed at the Prado Museum is a copy of Leonardo's *Mona Lisa* that was undertaken by his apprentice. In the studios of established masters such as Velázquez and Rembrandt van Rijn (1606–1669), technicians were trained to perform the more laborious tasks including backgrounds, patterns of dresses, leaving the master to undertake the finer aspects of a painting. In the eighteenth century, in order to gain an understanding of the technique of drawing, J.M.W. Turner (1775–1851) set his students the task of copying from his own drawings. Stephen Farthing, curator of *Drawing from Turner* at Tate Britain (2006) explained that the importance of copying from Old Masters in the Academies was 'not to forge, but to try to understand' (http://www.tate.org.uk/whats-on/tate-britain/exhibition/drawing-turner/drawing-turner-copying-turner).

1.3.7 Technical Examination of Artworks

Scanning of artworks is a significant component for understanding the health of a painting, to assist in conservation and to understand how a painting was made. Galleries and museums are increasingly using digital scanning methods to measure the surface of paintings (Case Study 5: Capturing Texture of Paintings for Museum and Heritage), as demonstrated by Tim Zaman *et al.* (2014), who was working with the Mauritshuis (www.maritshuis.nl), the Kröller-Müller Museum (http://krollermuller.nl/visit) and the Rijksmuseum (https://www.rijksmuseum.nl/en) to undertake the scanning of the works by Rembrandt and Van Gogh. Then the Canon Océ Group made a series of high-resolution colour 3D prints (http://www.3dartistonline.com/news/2013/09/3d-printing-fine-art-reproductions). The digital scanning revealed the sculptural qualities of the brushstrokes and different brushes and tools employed by the artists (see Figure 1.11).

In 1968, The Rembrandt Research Project (RRP) (http://www.rembrandtresearchproject.org) was established in order to reduce the huge number of supposed Rembrandt forgeries. It used specialist scanning and art historical investigations to categorise and discover new facts about the works of Rembrandt. This was a mammoth undertaking, resulting in six volumes entitled *A Corpus of Rembrandt Paintings*, of which the sixth is a revision of the collection (http://www.springer.com/series/6494). As a result, through re-evaluating previously attributed works of art, the RRP

Figure 1.11 Textured reproduction of Van Gogh's *Flowers in a Blue Vase* (1887). The high-resolution 3D prints were made by the Océ Canon Group (courtesy: Tim Zaman).

became the authoritative organisation for the identification and authentication of Rembrandt's works.

The method of assessing its provenance was based on both technical examination using scientific aids, such as X-ray radiography, infrared imaging, alongside traditional and historical insights and connoisseurship using, 'judgements […] largely based on intuitively applied criteria concerning style, brushwork and quality and taking into account every piece of evidence, that whilst not conclusive if taken separately provided a more compelling account' (White, 2015). Whilst the Rembrandt Database has incorporated a bulk of the RRP, the aim of the joint initiative of the RKD (Netherlands Institute for Art History) (www.rkd.nl) and the Royal Picture Gallery Mauritshuis (www.mauritshuis.nl) in The Hague, the Netherlands, is to work as a repository for all research undertaken into Rembrandt. In terms of documentation it lists a wide range of infrared, radiographic, other imaging such as stereomicroscopy, raking light, ultraviolet light, sample analyses and analyses of canvas and panels.

One could also ask, 'with all this data available, what could experts do with it?' As well as identifying forgeries, how could the data be useful to understand how Rembrandt painted? Did he use a particular brush stroke or geometry for creating a face? During a recent collaborative project entitled *The Next Rembrandt* (https://www.nextrembrandt.com) between Microsoft and ING, Delft University of Technology in the Netherlands, Dutch museums Mauritshuis and Rembrandthuis posed the question, "What would a new Rembrandt painting look like if we could use all the existing data?" According to the eminent Rembrandt expert, Ernst van de Wetering of the RRP, there is 'no such thing as a typical Rembrandt, each painting is unusual in its own way' (White, 2015). The goal of the project was to set about creating an entirely new picture based on the style of Rembrandt and using 168 263 Rembrandt painting fragments to create a new picture. Joris Dik of the Technical University Delft, when considering the methods used to create a new Rembrandt, started by using all the existing data and then designed an algorithm to identify and classify the most typical features. They also used data from the 3D scans to create texture that emulated the brushstrokes, 'We looked at a number of Rembrandt paintings, and we scanned their surface texture, their elemental composition, and what kinds of pigments were used. That's the kind of information you need if you want to generate a painting by Rembrandt virtually' (www.nextrembrandt.com). The data-generated file was printed using an Océ colour UV flatbed Arizona printer, reproducing all the colours and brush strokes that were digitally generated from the data. Thirteen layers were printed to create the texture with a coloured layer on top to add the detail. The result is startling and appears to be of a subject and style painted by Rembrandt. What might we learn from this, or is this just an interesting project? If a visitor to a gallery is unaware of the painting as a construction, how might they connect with the painting as an artwork *experience*?

1.4 The Authenticity of the Image and Object and Perception of Things

Throughout ancient civilisations, different cultures and groups have incorporated additional elements and dimensions to decorate utensils, jewellery, buildings and clothing. Learning skills and trades through manual and technical copying, trial and error, are examples of a transfer of traditional skills from maker to maker, material to object. Clothing was designed to be functional, beautiful and decorative, and using materials that were readily to hand (skins, fur, feathers, woven materials). A visit to a museum of artefacts, such as the Pit Rivers Museum in Oxford (https://www.prm.ox.ac.uk), reveals drawers and cabinets that are crammed with strange and curious archaeological and ethnographic objects from around the world. This museum could be considered as a rich resource dedicated to material culture, demonstrating how objects and artefacts were created with whatever materials were to hand; textured surfaces with bas-, mid-, and high-relief have been a constant denominator between cultures.

As demonstrated in Figure 1.12, 3D printing used for fashion, an eighteenth century protective waterproof coat made from animal skin or a cloak made from feather for rituals, each demonstrates a

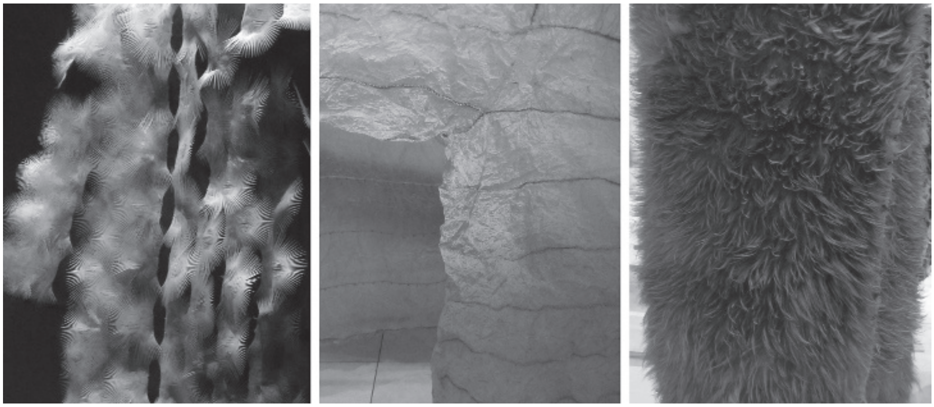


Figure 1.12 (Left) Dress from *Voltage Haute Couture* (2013), Iris van Herpen in collaboration with Philip Beesley made from polyester microfibre and polyester foam. (Iris van Herpen is one of the leading fashion designers using 3D printing to create flexible 3D printed dresses. Her collaborations include material collaboration with Philip Beesley, Neri Oxman of the MIT Media Lab, as well as Keren Oxman and Professor Craig Carter of MIT with Stratasys, and architect Julia Koerner with Materialise.) (Middle) Gut Parka (circa 1980) waterproof coats made from the intestines of sea mammals. They were originally associated with feasts and rituals and considered as garments that possessed the power to protect the wearer from misfortune and protect them from bad weather, Alaska. (Right) Cloak of feathers from Kiwi birds (circa 1914), New Zealand.

different material and tactile quality for different applications. In contemporary culture, designers continue to work with many different materials and methods for fabricating objects. A visit to a contemporary design museum, a couture house, or end of year student show will demonstrate the many ways artists, craftspeople and designers are drawn to combinations, richness and varieties of colours, materials and textures. How do high-value items become translatable into objects that are designed for reproduction and mass consumption? Does mass consumption require a cheapening in quality? What are the materials and surfaces that we are drawn to? Or would wish to keep? A quick look around a typical office raises the question: can we improve on the things that surround us? Modernity (printing, photography and cinema) has enabled the mass reproduction of objects, eliminating the authenticity and authority they initially had. In technical processes we use cameras and scanners that would allow us to see things that were invisible to the naked eye and that change inevitably the perception of the actual object. Technical reproductions such as lithographs, printouts and videos would place the copied object in a remote context far from the original (Benjamin, 1936).

It seems that culture has moved to a place where the average is the commonplace, uniqueness has been replaced by universal equality and authenticity ceases to be applicable to artistic expressions. Do reproductions lack a sense of aura? Are these just empty containers without a place in material culture or tradition? If this is the case, is there any way of finding anthropological value in reproductions?

If we work under the prior assumption that authenticity can be culturally constructed, that is of a socially intangible value, we may then be able to bring to life reproductions by involving entire communities into their creation. The sense of accomplishment attached to reproductions adds value to them (social relationships with objects) and it could possibly validate their authority or generate a new aura (ACCORD is an Archaeology Community Co-Production of Research Data, Stuart Jeffrey, https://accordproject.wordpress.com). Our visual system has been trained to recognize materials based on their appearance and even though we may be easily deceived by *trompe l'oeil* and optical illusions, we are able to compensate for our weaknesses readily. Just by looking at objects we form ideas in ourselves of their material composition. For instance, we quickly make estimates of different material properties such as uniformity (rough, porous, coarse, smooth, grainy, bumpy, corrugated, spiky, slippery), luminosity (cloudy, opaque, matte, brilliant, shiny, reflective, transparent), hardness (soft, stiff, flexible, elastic, brittle), viscosity (dense, solid, liquid, jelly, oily, firm), materiality/substantiality (silky, flaky, fibrous, feathered, interwoven, crystalline) and temperature (warm, hot, frosted, icy), among others.

We are capable of detecting many complex stimuli from an object, but our brain can resolve just a certain number of them. Elements such as perspective, translucency and colour, texture and shape-metamers can play tricks on our perception. Artists have long known this and have challenged the laws of physics to take advantage of our confusion (Case Study 7: *Trompe l'Oeil*). By mixing pigments, materials and painting techniques, they have been able to recreate the sensation of velvet, the depth of a room, the lightness of veils or the influence of forces such as gravity. How do we find the right balance before it becomes vulgar or cartoonish? Maybe that is what separates artists from amateurs.

Given the inability of controlling viewing environments outside our laboratories or workshops, we need to have a wide range of parameters in our creations that are still pleasing under different viewing conditions. For example, velvet still needs to be perceived as velvet no matter what the lighting source or the viewing position is. Achieving such a wide bandwidth of perceptual attributes in our creations demands a high level of understanding of our limitations.

Preliminary studies have shown that human observers are willing to make compromises regarding print quality in 2D prints but are stricter when it comes to the evaluation of relief or 3D prints. It seems that the closer we get to representing reality the more demanding and pernickety observers become. When we look at 2D representations of the real world, we know (consciously or unconsciously) that they are just that: representations. Therefore, we seem to be more forgiving and more ready to make concessions with a lack of detail and misrepresentation, as they are practically just a 'caricature' of our reality. On the other hand, we are more susceptible to artefacts in representations made in higher dimensions.

When we are called to judge the accuracy of the reproduction of scenes and objects, we tend to mix our understanding of them with our association and memories. Are they linked to a pleasant experience? Were they part of our childhood? Do they bring us back to a bad souvenir? Our understanding of things is based on our quotidian experiences with them. Nevertheless, we can still perform and rely on psychophysical experiments for evaluation as there are ways to avoid these limitations to a certain degree. A great deal of research has concentrated on making recommendations about test images, viewing conditions and the kind of questions that need to be asked in order to have successful psychophysical test results with a very low variability.

Intuitively, reproducing shapes and forms gives the impression that it is easier (from a technological point of view) than reproducing appearances but, as one can imagine, mathematical (objective) accuracy in reproduction does not guarantee a successful reproduction. This can be due to the mathematical part not being mature enough to quantify the subtleties of surface perception or because measuring perception of reproduced materials is so convoluted that technical accuracy will never measure what the subject entails.

We argue that accuracy is not necessarily required for most reproductions, as a certain degree of interpretation of things may be more valuable and more welcome than a cold replica. A clear case where interpretation is fundamental has been investigated by Studios Durero and their Didu project (http://www.estudiosdurero.com/estudios_durero/opencms/Presentaciones/didu.html?idioma=en), which attempts to make Old Master paintings accessible to visually impaired people through relief prints. Their approach could be considered as semantic – what is the salient information that is important? Their designers work along with art specialists and a group of visually impaired people to either exaggerate textures already present in a painting or create new ones that would be visually relevant but need to be simplified to be understood by blind participants.

1.5 Current Industrial and Mechanical Methods to Reproduce the Appearance of Texture

In the age of industrial reproduction, printers have struggled to represent natural surface textures that can already be achieved so creatively by artists. From a technological point of view, our task is to observe the behaviour, gestures, tools and techniques artists have mastered across many centuries and to programme our machines (printers, displays) to develop similar tricks to transform their resources into surfaces that are perceptually analogous. The interest is no longer in reproduction of fine art prints but using similar concepts involved in such creations to be able to reproduce the appearances of different materials.

As part of the course of (technological) evolution of humans across different fields, technology is beginning to study ways of reproducing and communicating material perception in the same way that nature and artists have previously mastered. To some extent, resources in printing are still highly limited as the robot is unable to emulate the movement, nuances and autographic gestures of human fingertips, hands, wrist and arm that is adept at holding a pencil or brush. However, for the human body to learn a craft or a skill may take many years – as exampled in the art of Chinese calligraphy, where children start to learn at school and then move to being an apprentice to a master. The human body may become adept to almost every circumstance given time and practice. However, to emulate craft through reproductive methods, technologies, substrates and inks may be developed to achieve similar results. Something that plays to our advantage is that as our senses are equally limited in finding the right recipe for the blend is the motivation for current and future research.

Therefore, why try to mimic existing textures industrially? What is industrial reproduction good for? Parallels can be made with the transition from analogue to digital printing. In this new era packed with personalised items and easy access to technology we can anticipate more and more creative opportunities and new methods for artistic and decorative applications. Technology and art now have common grounds that morph rapidly, making it difficult to keep up to date. New trends come and go, but what remains is the idea of being able to recreate existing stuff based on or with other existing stuff.

Artists took centuries to master dimensionality and transparency and one could wonder how long it will take us to replicate that, and, looking to the future, how long it will take us to master material appearance reproduction in contemporary reproductions. The process is somewhat overwhelming, maybe due to the huge amount of variables involved, maybe due to the flow of virtual of information available everywhere in the planet or perhaps because of the different technologies available to play around and experiment with in a more creative sense.

Nevertheless, current 3D print researchers have taken a more pragmatic approach, leaving behind the aesthetics to produce functional pieces that were typically constructed by costly industrial processes. Printing technologies are now moving away from the reproduction of entire objects to concentrate on macrotextural elements and some are concentrating on microtextural aspects that will allow printing to conquer the appearance of reproduction fields in the future. For the moment, there is no magical solution to mimic relatively simple but typically hard-to-reproduce materials such as velvet and hair, not only in printing but also in computer graphics where the images on screen still look synthetic.

1.5.1 2D Printing Methods

In planar printing we can try to emulate the artists' approach to texture reproduction by controlling the way the ink interacts with the media. The printing industry has made an effort to provide more dimensions for creators by moving beyond the cyan, magenta, yellow and black process inks, and proposing distinct colours, translucency levels, and gloss options. Moreover, the usage of media with different rugosity properties is currently supported by many printing processes. However, most artworks have a dimensionality that cannot be conveyed with a flat 2D print. To go beyond planar printing, we can print different layers of ink to control the surface and subsurface scattering of light and therefore generate different visual effects, similar to the ones seen in artists' conceptions, and even decide to either keep or discard the effect of the supporting substrate.

For centuries most of the first printing technologies were based on the use of plates and blocks that contained the information to be printed in relief. Such plates were covered with ink and pressed against the media to produce the printout. Japanese techniques such as the tonal woodblock printing of Ukiyo-e would even allow the use of different colours in the same print, where the colour range of the final print depended on the choice of the printer and the complexity of the image. As newer alternatives for printing appeared, an interest in the printing of special effects developed. After graphic design consolidated as a profession during the beginning of the twentieth century, digital techniques to create different textures such as embossing emerged. The packaging industry (offset printing) started to use textured zones in the wrapping of products to make them more appealing because tangible materials leave a deeper imprint in the brain as it involves more emotional processing. Presses composed of several stations are capable of adding different effects by gluing foils, marking the media and printing varnish.

The advantages of digital printing versus analogue printing mainly consist of improved versatility, personalisation and better interfacing with other technological processes. The importance of continuing the development of digital machines that handle multiple printing materials and techniques is to keep these advantages of the digital world to cover different aspects needed for material reproduction in one (or a few) steps.

Printers and printmakers certainly appreciate the fine balance between image, matrix, ink and paper that may impact the surface dimensions, either by the translucency, opacity, gloss or viscosity of the ink, and thus the 2.5D qualities of the ink and paper relationship. From the three essential print processes (relief, intaglio and graphic), there has developed an enormous range of manual and subsequently mechanical print processes, including screenprinting, rotogravure and flexography. Each demonstrates different textural qualities, albeit on a microscale. Furthermore, the impact of the matrix or plate, such as the edge of a lithostone or embossing from a woodblock, letterpress or engraved copper plate, can also create added dimensions. Although inkjet printing is assumed to be a non-impact process, adding a nanolayer of ink to the paper by a skilled digital printmaker will change its surface qualities (Case Study 13: Analogue Printing Methods).

1.5.2 The Emergence of 3D Printing

Thanks to new technologies to render objects in multiple dimensions we have the potential to show micro details, texture, and different illumination settings to reproduce the qualities and characteristics of the originals. Regardless of the recent advances in the 3D market, the issues of printing high-quality details, colours and reflection effects is far from being solved. Many assumptions applied to 2D technologies may well have hampered the development of 3D printing, as the complexities of the 3D workflow have certainly been underestimated. Not only have printing techniques begun to languish since their creation, but also the development of higher-dimensional displays and scanners have been impacted and therefore the entire workflow has suffered an anachronistic evolution.

In a way, the printing industry has always served as the protagonist in historical, social and political revolutions, and we are about to experience a significant change in the way we look at, make and consume products over the next decade.

Today, the maturity of 2D printing technologies has enabled a switch in research priorities to 3D printing methodologies. The market of 3D print has found a place in the areas of rapid prototyping and additive manufacturing and the technological advancements have concentrated on building functional objects where aspects such as colour, detail resolution and other important material appearance properties have been neglected. Despite its aesthetic limitations, additive manufacturing provides the technology needed to unite materials and media.

The history of additive manufacturing dates back to the late 1950s and early 1960s when the first patents describing printing 3D objects were submitted (Munz, 1956). The US Patent issued to John

Munz in 1956 described a process that he called ‘photo-glyph recording’ to produce three-dimensional objects using a light-sensitive emulsion. In the 1950s and 1960s, the DuPont Company gained a number of patents for their experiments using two laser beams of differing wavelength to solidify a photo polymer resin. More than 20 years passed before the process gained any commercial interest when Charles W. Hull commercialised his invention called stereolithography in the 1980s (the term ‘stereolithography’ was introduced by Chuck Hull in his patent in 1986) and established 3D Systems. Other startups based on similar 3D printing techniques were launched (mainly in United States and Japan) but just a few have survived until the 2000s (Stratasys, ZCorp, 3D Systems). The lack of user-friendly applications and high costs of materials and processes seem to have influenced the initial delay in the development of this technology.

It was not until 2009 that an ASTM (American Society for Testing and Materials) Committee, called ‘F42 on Additive Manufacturing Technologies’, was established to join efforts in the standardization of terminology, design, materials and processes. In 2011, the ASTM F42 Committee and the ISO Technical Committee 261 on Additive Manufacturing announced an agreement of cooperation to avoid duplication of tasks. The involvement of two standardization communities shows the interest of the industry and encourages 3D print practitioners to continue their work. Regarding the colour and more general reflection aspects, the International Color Consortium (ICC) has also recently contributed by proposing a new way of thinking (iccMAX) about the typical colour management undertaken in 2D printing by including reflection properties that were less important before. Its adoption by the industry is still yet to be seen as not only the format of colour profiles change but also other modules in the classic colour pipeline or colour management system (CMS). Despite the efforts made until now, a universal file format and standard workflow to communicate reflection and geometric properties has not been established. Printers have either adapted a stereolithography CAD format created by 3D Systems called STL, or have their own proprietary format that works on a handful of machines. STL files describe only the surface geometry of a 3D object without any representation of colour or texture. A newer digital 3D file type that includes colour is commonly known as the Virtual Reality Markup Language (VRML), designed mostly for Internet and virtual reality applications. In 2005, the consortium Web3D proposed an update of VRML called Extensible 3D (X3D) but since then big players have left the consortium and created their own formats, namely, Intel with U3D, Microsoft with XAML and Dassault Systèmes with 3DXML. The amount of options regarding file formats, file compressing protocols, colour/features transformations and the variety of parameters available in the 3D field is overwhelming, not to mention the fact that quality standards to evaluate performance have not yet been put in place. Past experiences in printing, such as colour management back in the 1980s and 1990s show that the implementation of standards helps to benchmark products and processes as well as to communicate with customers and other makers. A full adoption of 3D printing and other 3D technologies may be hindered by the delays in putting together a clear standard workflow and quality targets. On the other hand, relief printing has been able to remain closer to what is already known in terms of file formats and standards, but the integration of 3D technologies into a relief workflow (or even the merger of both technologies) is a reality and we need to be aware of the weaknesses in the area.

Meanwhile the 3D printing industry continues to grow; since 2010 new and financially stronger companies have emerged with a range of cheaper printers (for example, Makerbot, Bits from Bytes) that produce more appealing content creation environments, whilst being user-friendly enough to attract a good percentage of the consumer market for easy upload to the leading 3D print bureaus (for example, Shapeways, Make XYZ, Sculpteo, Ponoko). Traditional players in the printing industry such as Roland, Canon and Hewlett-Packard offer subtle additions that can change the surface of prints, for example, to build surfaces with contrasting visual effects made of varnishes or special inks (metallic, translucent, opaque). In 2014, Roland, Canon and Hewlett-Packard announced their intention of moving into the 3D printing field. In 2014, Roland DG introduced a desktop ARM-10 3D Printer that could be used in conjunction with the SRM-20 desktop milling machine. In 2015 Canon entered into an agreement with 3D Systems and in 2016 HP launched their HP Jet Fusion 3D 3200 Printer. New markets have started to develop around the concept of 2D+ (2.5D, 3D) printing as an option to diversify their production and integrate different technologies into one single product. For example, in 2016, Ricoh launched the AMS5500P Printer, which can print using different materials to build functional parts for product testing.

On one hand, we would like to have more options of 2.5D and 3D printing materials but, on the other hand, there is the question about sustainability and ethical usage of toxic substances, petrol-based derivatives, and their biodegradability and recyclability. These concerns go beyond the printing materials as most 3D printers are 'energy hogs', as concluded by scientists at Loughborough University (2009) (http://sustainabilityworkshop.autodesk.com/blog/environmental-impacts-3d-printing), if compared to traditional casting, moulding, milling or machining. Moreover, the waste generated from the support materials in 3D printing is also more important than what is produced in classic industrial processes. Unhealthy air emissions due to plastic melting, solvents and toxic by-products, and possible contact with food or skin, are also significant factors.

New biodegradable printing materials are slowly becoming available, but their usage is not yet widely adopted. In 2014, 3D systems launched the Ekocycle Cube Printer, a machine that works with filament that is composed of 25% recycled material. An open source initiative called RecycleBot (http://www.thingiverse.com/thing:12948) converts household plastic waste into usable material to be fed into small-scale 3D printers. There is also a project called 3D Print Canal House (http://3dprintcanalhouse.com) that aims to 3D print an entire building with Macromelt, a printing material made of 80% vegetable oil. Despite these few efforts to use biodegradable options in printing, these alternatives may be less desirable, as these 'biodegradable' options are usually corn-based and other essential food sources that also impact on poor countries where knock-on effects such as food price rises and soil erosion can occur as a result. Furthermore, there remain other health, ethical and legal aspects yet to be addressed including: regulations, licensing, counterfeiting, bioprinting, gun legislation and drug abuse.

Aside from the complex issues surrounding environmental sustainability, there is also discussion about economic sustainability. Taking into account that the cost of 3D printers range from a couple of hundred to several hundred thousand dollars, printing materials also range from US$15 to US$800 per kilogram, and finished objects printed by a third party commercial vendor are an added cost. For example, to print a 3D object with dimensions of 15 cm × 4 cm × 4 cm (with a printed surface of 272 cm^2 and volume of 240 cm^3), could significantly range in cost depending on the type of material used. The following table provides a comparison guide.

Material	Process	Cost
Nylon (polyamide)	Selective laser sintering (SLS)	$7
ABS (acrylonitrile-butadiene styrene) or PLA (PLA (polylactic acid)	Fused deposition modelling (FDM)	$60
Mineral powder	Inkjet 3D printing or drop-on-powder	$220
Epoxy resin	Stereolithography (SLA)	$350
Alumide (polyamide powder and fine aluminium particles)	Selective laser sintering (SLS)	$420
Photopolymer resins	Polyjet matrix printing	$2000
Stainless steel	Direct metal laser sintering	$3500

This cost may increase depending on the finish, the addition of colour and post-processing. Although makers can benefit from no hardware costs and short runs, there is also the question of margins and profitability. In 2012 Amazon opened a 3D store called 3DLT so that customers could upload 3D files and buy their products, but it was closed a few years after. Around the same time Threeding and Pinshape emerged to facilitate the trade of 3D models, similar to the service that was expected from 3DLT. Another business model has been developed by Materialise and Prodways who specialise in additive manufacturing to produce prototypes for industrial partners or to provide the software to others with additive manufacturing capacities to produce prototypes for their own customers. Sculpteo and

Shapeways offer a range of online 3D printing services and a wide variety of printing materials. Other printing providers such as Project Eiger (http://www.projecteiger.com) and Estudios Durero (http://didu.estudiosdurero.com) provide 2.5D printing for a specialised range of applications.

We can find more examples in the open source community that provide repository and file exchange services to their customers. However, the printing applications and opportunities still feels underexplored and it seems for the well-established companies the actual printing exploration is left to hobbyists and geeks. Political leaders around the globe have added 3D printing as one of their priorities in the belief that there are opportunities for change and impact on current manufacturing practices. Barak Obama announced in 2013 that 3D printing had 'the potential to revolutionize the way we make almost everything'. In 2014, he hosted a *Maker Faire* in the White House to promote Fab Labs (fabrication labs). Neil Gershenfeld, the creator of Fab Labs, defines Fab Labs as places where we can make 'almost anything' that will bring us to 'a new digital revolution'. These labs are equipped with computer-controlled tools such as CNC, 3D printers, scanners and laser cutters. To illustrate his point he makes an analogy between Fab Labs and the history of computing. By the time personal computers were released into the home computing market, the World Wide Web had already been developed by networks of scientists to share their research on minicomputers many years before. This phenomenon resulted in almost no delay in integrating the two technologies and develop their applications. In the same way, Fab Labs emulate today what personal fabricators will eventually do in the future and 2.5D/3D printing is an important part of that. However, in order to understand 2+D printing as a part of the future of sustainable manufacturing, both from an environmental and economic perspective, the different technologies must support new models of sustainable businesses (circular economies) and supply chains and versatile pipelines.

Regardless of the experience gained during recent years, the many issues of quality in 3D printing are far from being solved. Formal studies into the different constraints that exist in 3D printing have only taken place in the last twenty to thirty years. During the recent explosion and hype in the press regarding the future of 3D printing and its applications, we have overlooked the important details of reality in exchange for fast production, functionality, costs and probably an easier expansion and acceptance of a printed 3D world. The macrogeometry of things has taken over the reproduction of objects, forgetting that our senses are used to seeing the real world with a pinpoint degree of resolution. For the moment, the printing industry has concentrated on making objects and prototypes that convey more aesthetic qualities and is just beginning to develop materials for printing objects that are functional.

Even though 3D printed objects are commonly limited to one colour, which is the same as the printing material, some technologies offer a reduced colour palette that can be used in a per-area basis. If more realistic colours or surface effects are required, manual finishing processes are used to achieve the desired appearance. Moreover, undesired rough surfaces also need to be used at a polishing/finishing stage. Besides the lack of quality (aesthetically speaking), the manual processes involved in the final step make a full colour 3D or polished object an expensive and requires the skills of the technician or craftsperson. Mastering the technical aspects of 3D printing is not enough for the production of artefacts, especially if related to cultural heritage, where a high degree of accuracy is required. Creating accurate replicas of historical objects is fundamental to ensuring the cultural, historical and archaeological context and as part of the narrative when curating museum objects.

1.6 Conclusion

In this introduction we have explored the relationship between images, pictures and reproductions. We have begun to explore different ways to describe 2.5D, the relationship between texture, material and object, our emotional and perceptual relationship with materials, how artists convey the appearance of materials and how materials can be measured and quantified. One can start by a negative and suggest that it is not about printing objects (3D) or about printing images (2D), but something between the two – or more simply put, the relationship between the surface and the substrate, and textural attributes of a material and the object.

2.5D printing has not yet abandoned several aspects borrowed from 2D printing but it has adapted them to the new challenges. Likewise, 3D printing is not ready to implement what 2.5D brings to the field as it adds another layer of complexity to the already complicated field of 3D. Therefore 2.5D printing remains for the moment as a standalone technology that may merge in parallel to 3D in the future for the sake of multimaterial, multifunctional, multiapplications, multidimensional, multiplatform printing.

If we consider 2.5D or relief printing as the bridge that connects 2D and 3D printing, then, on the one hand, we have 2D printing, which lacks enough degrees of freedom to cover the complexity of reality and, on the other hand, we have 3D printing with an overwhelming amount of variables and unable to concentrate on more subtle aspects. We as humans are complex subjects and our reactions are not only physical but also psychological. Our memory of shapes, colours, textures, our previous experiences, our cultural background, as well as our physical skills and limitations play important roles in the overall perception of an object. 2.5D or relief printing concentrates on studying the external layer(s) or skin of objects as this is the part that is more in contact with our senses. This superficial layer contains the microstructural information needed to understand material properties such as texture and reflection. Emulating the fine details contained in surfaces is the key to bridging the gap between an artificial and a natural reproduction.

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