

# 1

## Image Processing

### 1.1 Introduction

In the past there was only one choice of recording medium, 'Film'. It was available in a number of sizes normally 10" x 8" and 5" x 4" sheet film, 120 and 220 roll film and of course 35 mm. This was then available in a various emulsions: colour negative, reversal, black and white and in a number of speeds (sensitivity). Although limited film stocks are still available in small numbers, film no longer has a mass-market appeal and more importantly, is no longer be used by law enforcement agencies.

Today the advent of the digital sensor has made all these 'film' choices and more, available at the touch of a few buttons. Yet it could be argued that instead of making the task easier, it has made the choice harder. For example, today's camera manufacturers not only produce various size sensors, but each has its own particular sensor design and its own in-house post production software.

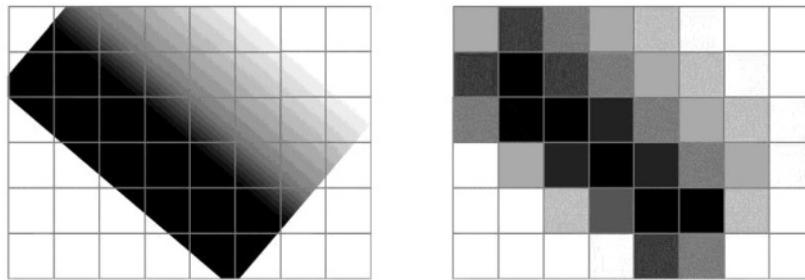
As a forensic photographer the question is how we decide which system is fit for purpose and to answer that question, we must have an understanding of the very heart of modern camera technology, the sensor and the digital process.

I shall start with definitions of the digital image and an explanation of digital image acquisition; then I will discuss some simple examples of things we commonly do to images that might not be thought of as image processing, which will introduce the fundamental concepts of what image processing is about. I'll consider both the reactive and proactive uses of image processing – put another way, examples of restoration processes and enhancement processes – and along the way we'll encounter analysis processes and synthesis processes. All these terms will be defined, but it may be more understandable if their explanation comes after some practical examples.

Image processing is a term that covers a very large number of operations that may be performed on an image, some of which the photographer will have control of, some of which a technician may have control of, and some of which will be dictated by the equipment therefore in practice, may be out of the control of those using it. Image processing occurs at every stage between exposing a photograph and finally presenting it to the end user. It is, therefore, unavoidable. At the very least a basic understanding of image processing is essential, even if only to assist with choosing from the many settings in a digital camera's set up and shooting menus. Many users may not even consider the latter as image processing, as the term is more commonly applied to the treatment of images once they have been captured. With some relatively simple processes astonishing results may be achieved from photographs that may initially appear of limited use. An advanced knowledge of image processing options may even revolutionise how you approach photography from the outset. Although the broad term *image processing* also applies to analogue photography (for example various different film developers may be chosen for different effects, such as high contrast or high acutance (sharpness)) we will only consider *digital* image processing here. In a small volume such as this, we can only scratch the surface of this vast subject with its myriad options. I will introduce the fundamental concepts common to all digital imaging: the digital image, the imaging chain, the classes of operations and examples of where in the imaging chain they may be encountered. In the forensic context the integrity and reliability of images is of the utmost importance, particularly when images provide primary evidence. So we must consider ways to ensure integrity and prove reliability: I will discuss the concepts of workflow, the audit trail, archiving and storage and direct you to published best practice guidelines and further reading. When discussing post-capture software I will most often refer to Adobe Photoshop because it is the most widely used application, but the principles apply to all image processing software.

## 1.2 The digital image

What is a digital image? It's a question I often ask photographers. The replies are many and varied but rarely do I receive a response similar to 'it's a set of binary numbers representing a scene', because that's not how people perceive images. We can see images, can't we? A set of binary data is altogether more abstract. But for the digital image on your memory card, or on your hard drive, or in the ether between your wireless devices: can you see it? No, you'll need a monitor or a printer to display it first. The camera's optics project a pattern of light onto an array of electronic sensors; the electronics convert the response signals into a set of binary data and, in the simplest concept, a monitor's electronics will convert the binary data into electrical signals, which are then sent to an array of, say, light emitting diodes (LEDs) to display as a pattern of light. The result will be a likeness of the thing photographed, a *representation* of the *scene*. Once it is accepted that the digital image is data



**Figure 1.1** Left: Image of object (smooth edges, continuous tone) projected onto array of square pixels. Right: digitised image after sampling and quantisation. Sampling leads to ‘blocky’ edges; quantisation produces discrete levels of grey and leads to blurred edges because the resulting grey level is a function of the average intensity at each pixel.

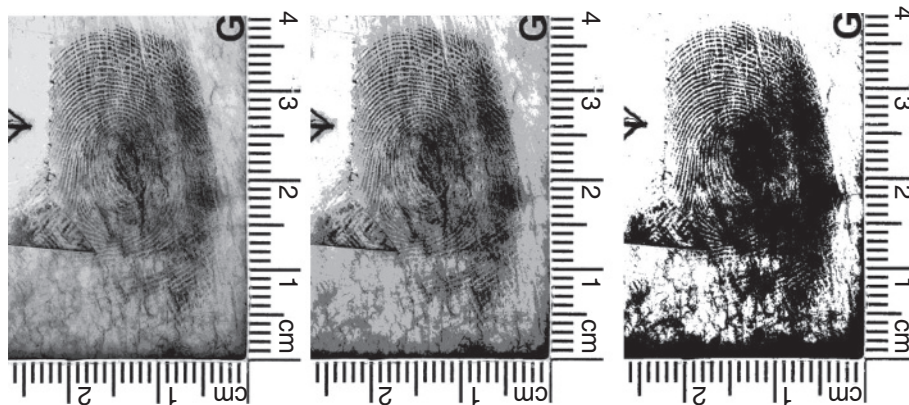
and that we can’t see data and therefore need some device in order to see the image, I suggest we can consider two important concepts: one, we can free ourselves of presumptions that an image appearing on one device, say, ‘computer screen A’, is any truer a representation than its appearance on another device, say, ‘computer screen B’, (unless both screens are calibrated to some independent standard), and two, the necessity for image processing, or data manipulation<sup>1</sup> becomes apparent.

### 1.3 Image acquisition

Although the digital camera is the most common device for acquiring a digital image, digital images may originate from other devices such as scanners, frame-grabbers from analogue video, and so on. Scanners, whether specialist film scanners or flat-bed desk-top scanners, are regularly used to digitise photographic negatives and prints in a hybrid workflow. Whatever the device, the fundamental processes of digital image acquisition are similar.

All processes of digital image acquisition involve two basic operations: sampling (measuring light intensity) and quantisation (assigning a discrete value to that measurement) (Figure 1.1). The number of locations at which light intensity can be measured (sampled) is set by the number of pixels a device has, which is usually stated as the pixel count. The convention is for cameras to be specified as, for example,  $4000 \times 3000$  pixels, or ‘12 megapixels’, where a megapixel is one million pixels. For scanners, the figure is stated as pixels per inch, both horizontally and vertically. The number of pixels largely defines

<sup>1</sup> The term *manipulation* is generally avoided when discussing forensic image processing as it is considered to imply malicious intent. The Oxford English Dictionary, however, also defines *manipulate* as ‘handle, treat, or use, especially skilfully’. I sometimes use the term provocatively to remind people that image data must be processed to be displayed and we need to consider the steps we have little control over (such as printer drivers) as well as those we have much control over (such as the use of Photoshop).



**Figure 1.2** Images of finger mark, recorded with bit depths of (left) 8, (middle) 2, and (right) 1, giving 256, 4 and 2 grey levels respectively. In order for us to perceive a monochrome image as having continuous tone, 8-bits are required, allowing  $2^8$ , that is 256, discrete values or grey levels. I will discuss file formats later in the chapter but it is worth noting here that different file formats may have, or allow, different bit depths. It is common for raw formats to utilise 10, 12 or 14 bits; TIFF may allow 8 or 16 bits, whilst JPEG is limited to 8 bits. Are extra bits necessary if we can't perceive the difference between several different values? Maybe (more on this later).

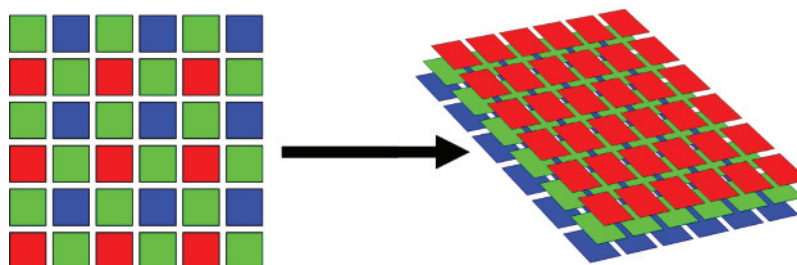
the spatial resolution of the resulting image (other factors include the optics employed in the formation of the image).

The number of values used to represent the light intensity at each location is limited by the *bit depth* of the device. *Bit* is an abbreviation of *binary digit*; the number of possible values will be a power of two. A 1-bit image can have only two possible pixel values: 0 or 1, that is black or white and nothing in between (Figure 1.2).

## 1.4 Colour images

In practice most of us use colour cameras. Pixels can't inherently 'see' colour. To record colour information individual pixels are overlaid with coloured filters, most commonly the three additive primary colours: red, green and blue (RGB), the filters being arranged in a regular mosaic pattern or *colour filter array* (CFA). Each individual pixel is therefore only able to respond to part of the colour spectrum. But when we look closely at the resulting image we find each pixel has values for each of the three primaries. The process of deriving the 'missing' two colour values for each pixel is called demosaicing<sup>2</sup> and is one of the first instances of image processing in the imaging chain. The result is, in

<sup>2</sup>Demosaicing involves processes of interpolation, 'filling in the gaps', and is common to the vast majority of colour cameras. Some people argue strongly that interpolation must be avoided, whilst being apparently oblivious to the fact that by their own definition two-thirds of every photograph they take is 'made up'! Cameras employing Foveon X3 sensors, where demosaicing is not necessary, are



**Figure 1.3** A typical Bayer colour filter array, laid over the sensor, means that each pixel only records part of the colour spectrum (left); full colour information for each pixel results from demosaicing (right).

effect, three overlaid monochrome images. Therefore colour images require  $3 \times 8$  (24) bits, or  $3 \times 16$  (48) bits, and so on (Figure 1.3). To add to the confusion, 24-bit colour images are often referred to as ‘8-bit’; 48-bit colour images ‘16-bit’, and so on.

Whether we’re dealing with greyscale or colour images, the outcome of the image acquisition process is a two-dimensional matrix of binary integers representing the scene photographed, where each integer represents a grey level (or each set of RGB integers represents a colour) and each position in the matrix represents a geometric location. Again, this concept of the digital image should assist the understanding of all that follows.

## 1.5 The imaging chain and workflow

The *imaging chain* is the series of devices between image acquisition, or capture (input), and final display (output) and workflow is the *direction of travel* through the imaging chain. If you take a photograph with a digital camera the chances are the first time you see the resulting image is on the screen on the back of the camera. The light projected onto the sensor by the lens has been sampled and quantised; the resulting digital image has been processed in-camera and signals sent to the camera screen. Already there are three links in the chain: image sensor, camera processor, camera screen. The chain can be considered to be made up of a series of links, where each link is ‘input–process–output’ and where the output of one link is the input to the next link. A simple, practical, scenario may involve taking a photograph and saving it in raw format, converting it to TIF format on a computer whilst viewing it on screen, and then printing it on a desktop printer. This involves the four major links of camera, computer, screen and printer.

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notable exceptions. Demosaicing could be considered to be a restoration process, but I suggest by strict definition it is a synthesis process.

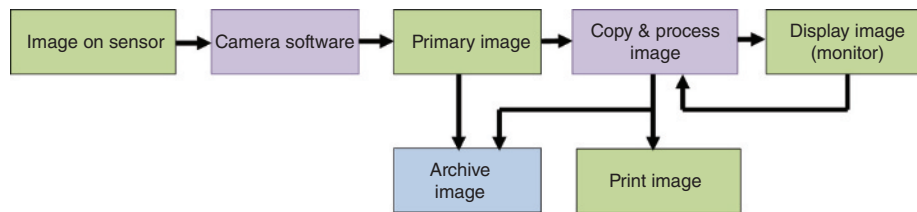


Figure 1.4 A typical imaging chain and workflow.

Each device will have its particular characteristics in terms of how it reproduces and displays the image data, and each device will therefore require the data to be processed somehow. Mostly this is done by the electronics and drivers associated with each device, over which the user has little control, though in many cases some control may be exerted via, say, an on-screen dialogue box. Possibly the simplest to understand (yet the most important) attribute of images is the reproduction of tones (brightness, contrast) and the most common image processes involve adjusting brightness and contrast in some way. An analogy with film photography is the two-link negative–positive black and white print process: the first link is the production of a negative image, where the tones of the *subject* are reversed; the second link is the production of a positive print, where the tones of the *negative* are reversed: the contrast and brightness are controlled at each stage by the level of exposure, the development conditions and the choice of emulsions of suitable grade (contrast); the reproduction of tones is described by a material’s characteristic curve. In comparison, a digital imaging device’s tone reproduction may be described by its transfer function although, in contrast to film manufacturers, the manufacturers of digital imaging devices rarely publish transfer functions. Resulting images may be modified by adjusting brightness and contrast or using levels or curves functions. Colour balance is maintained by treating each of the RGB images separately whilst aiming for neutral tones without colour casts. Even if our only concern is to maintain ‘correct’ tone and colour, some adjustment throughout the chain will be inevitable, especially if the final output is a print. Processing is necessary because of device-dependent colour reproduction characteristics. The RGB primaries of a computer screen are unlikely to match exactly those of the camera sensor, and neither will match the printer, which will print in the subtractive primaries of cyan, magenta and yellow (CMY),<sup>3</sup> at the very least, and may include several more colours. Many potential problems of colour reproduction can be avoided by employing good colour management. In simple terms, colour management is the practice of ensuring that the colour you see on screen is the most accurate representation of the colour the camera recorded, and that your resultant print is

<sup>3</sup> To push the previous point about interpolation, the conversion from RGB to CMY will involve the recalculation of *every* pixel value and, by definition, the alteration of *every* colour.

similarly colour-accurate. Detailed discussion of colour management is outside the scope of this volume, but the importance of maintaining accurate colour should be obvious. We should, however, consider the relatively simple question of how to achieve correct white balance.

## 1.6 White balance

When we look at a scene we have a remarkable ability to compensate for changes in the colour of the illuminant. I often use a piece of A4 white paper to illustrate the point to students in a room illuminated with a combination of fluorescent strip lights on the ceiling and diffuse daylight through the windows. I'll hold the paper in a corner of the room where it is lit mostly by the fluorescent lights and ask, 'what colour is the paper?' The answer, of course, is 'white'. I'll then move to the window, where the paper is lit almost exclusively by diffuse daylight and ask again, 'what colour is the paper?' Again, the answer is 'white'. The colour of the paper hasn't changed and we know that, but we do compensate for changes in the colour of the illuminant: daylight is relatively more blue and fluorescent lighting relatively more yellow. In effect, our brain equips us with an automatic white balance similar to the camera function of the same name. But whereas we experience a scene in the context of its full environment, the camera captures an image that becomes abstracted from that environment and viewed at some future time, most likely under different conditions. If we photograph the paper in the two locations, and we want the paper to appear white in both photographs, then we need to adjust the camera's white balance accordingly otherwise the paper may appear yellow or blue in one of the photographs. It is good practice to match the camera's white balance to the illuminant by choosing one of the standard presets so that the camera maintains neutral colour reproduction without colour casts. When we change the camera's white balance setting we are telling the camera's software to process the image so that colours in the image appear as we see them. Cameras' automatic white balance can be remarkably adept, but where colours are critical it is best to include a reference colour scale within the original image and choose a suitable white balance pre-set. The colour scale then provides an objective, device-independent reference, which can be relied upon and can aid colour correction (Figure 1.5). Colour correction may be considered a restoration process.

Where workflow is fully colour managed, it should be possible to rely on the tones and colours of images at each stage, but my experience of forensic photography in practice suggests fully colour-managed workflow is the exception. In many practical scenarios it is very difficult to maintain control of the full imaging chain: what happens to those carefully exposed and colour balanced crime scene images once they're burnt to a CD and sent out to the investigating officer; who is ensuring the accuracy of the officer's computer screen and printer? Again, this illustrates why it is useful to include a reference colour scale. Photoshop offers a couple of very useful quick fixes for images that have



**Figure 1.5** Colour scales (and linear scales) provide standard references, against which objects in the image may be compared.

minor exposure and colour errors: the levels and grey-picker tools. Before discussing them, we should stop to consider the image histogram.

## 1.7 Image histogram

The histogram is a graphical representation of the distribution of grey levels within an image (and is an example of the output of an analysis process). It is an excellent aid for judging exposure and I recommend selecting an image review mode on the camera to display the overall histogram (or, better still, the RGB histograms) along with the image. The horizontal axis represents the available grey levels from black, at the far left, to white, at the far right, and the vertical axis represents the number of pixels that possess each value. The histogram can therefore be used to judge whether an image is under-, over- or correctly-exposed: a ‘good’ histogram will show a wide distribution of grey levels (Figure 1.6).

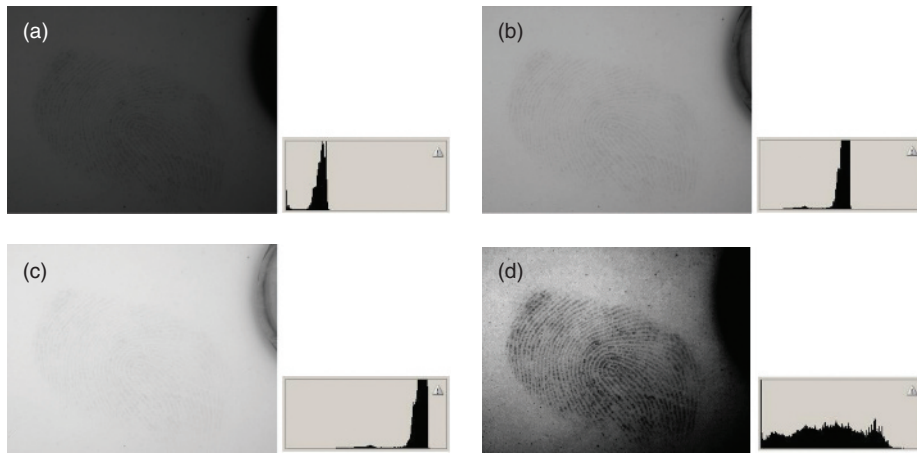
Histograms that show bunching of grey levels towards the extremes of the scale suggest some subject details have not been captured. If detail has not been captured it cannot be recovered, but in some circumstances detail may have been recorded that is not visible in the initial image.

### 1.7.1 Levels and grey-picker tools

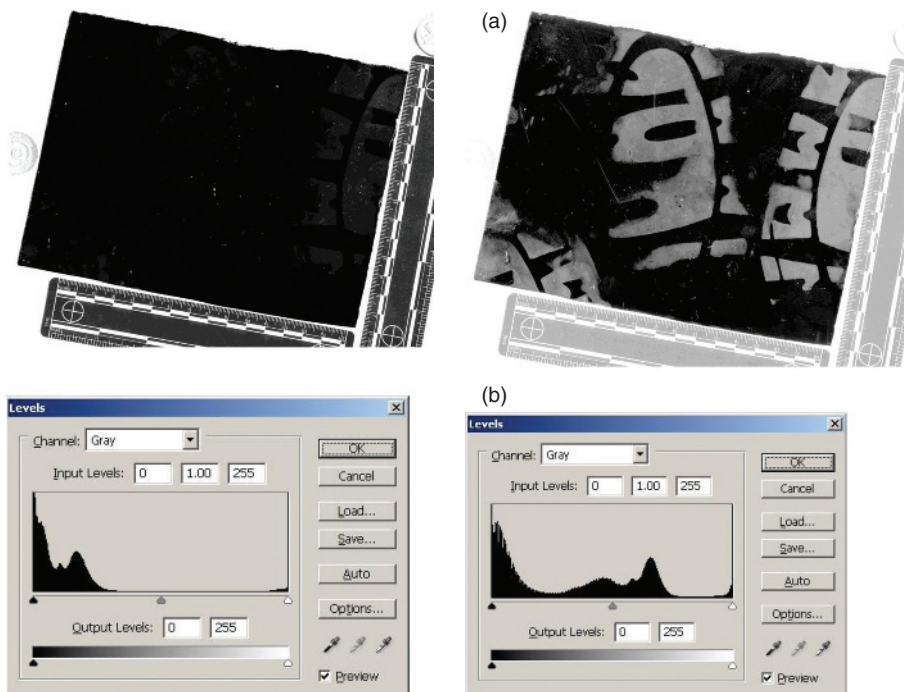
Where the only error is a minor exposure error, use Photoshop’s levels tool. When this is chosen, the image histogram is displayed, directly under which are three small triangles representing the black-, mid-grey- and white-points. These points may be moved along the scale by clicking and dragging to redistribute the grey levels (Figure 1.7).



1.7 IMAGE HISTOGRAM

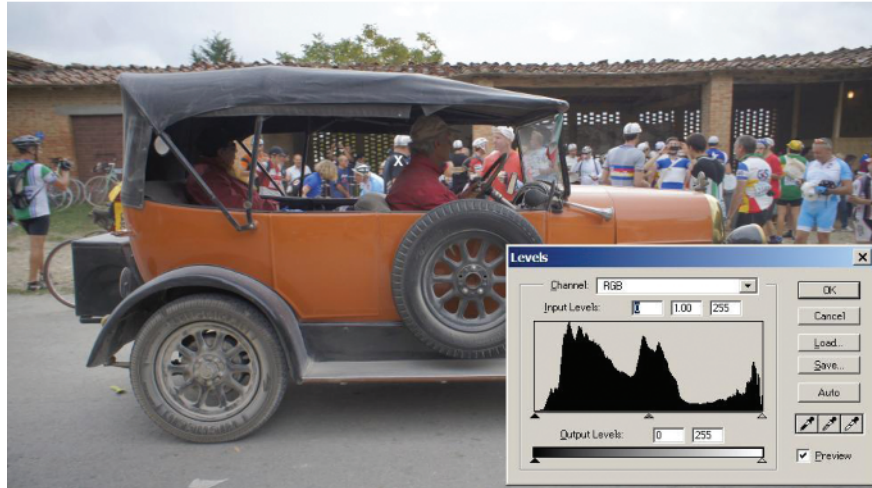


**Figure 1.6** (a) Dark, low contrast image and associated histogram. (b) Low contrast image and associated histogram. (c) Bright, low contrast image and associated histogram. (d) High contrast image and associated histogram.

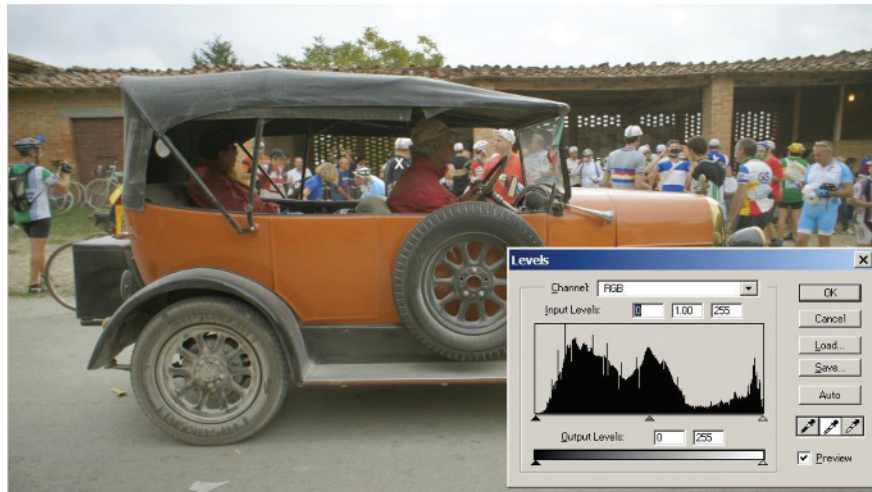


**Figure 1.7** Use of levels function. (a) The image as captured and the associated histogram. (b) Image processing using the level to enhance contrast and associated histogram.

(a)



(b)



**Figure 1.8** (a) Original image and histogram. The point in the image chosen to represent a neutral grey is indicated here by an 'X', near the centre of the image. (b) Image and histogram after colour adjustment using the grey picker.

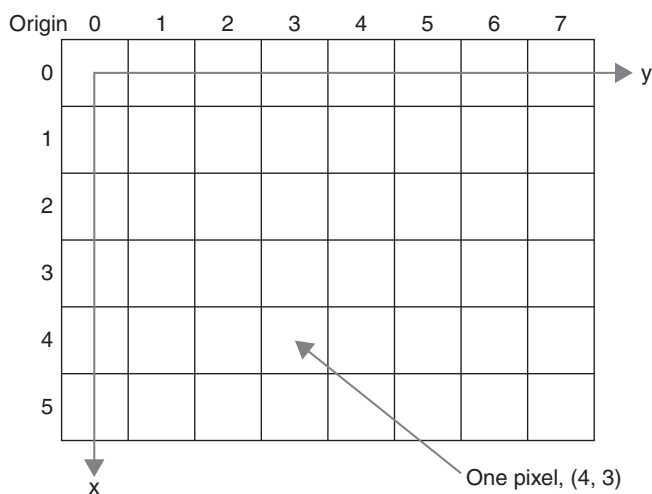
Where the problem is one of colour balance, use the grey-picker tool: first choose 'levels', then click on the grey-picker, and then choose a point in the image that ought to be mid-grey and click on that point. The result should be similar to having had the white balance on the camera set correctly in the first place (Figure 1.8).

Note that these quick fixes, and similar operations, should not be considered as replacements for choosing correct settings before taking photographs: the

‘corrected’ or ‘restored’ image comes at the expense of losing some image data and results may be inconsistent.

We have established the fundamental properties of digital images, the imaging chain and workflow. We have already covered some important image processing concepts, but in order to explore image processing in more depth let’s move onto what we may want to do with our images. I tend to classify forensic photography into two types: *reactive* (documentary) photography and *proactive* (examination-quality) photography. The former includes general crime scene photography and the photography of exhibits (items): the aim is to produce a ‘true to life’ record of the scene, as seen, that is with correct lighting, perspective, colour balance, contrast, and so on. The latter includes marks photography (finger marks, footwear marks, etc.), where the aim may be to produce the clearest possible image of a finger mark, distinct from the background surface on which it is deposited. The two classes are not mutually exclusive. Blood pattern analysis, bite marks by reflected ultraviolet radiation, night-time CCTV under infrared radiation, crash reconstruction via photogrammetry: these are just a few examples where the two-dimensional image may be analysed to provide three-dimensional information, and/or where we rely on photography to provide an accurate record of the inherently invisible. Conversely, it can be extremely important to demonstrate, via photographs, the accurate visual appearance of marks, for example finger marks in blood. But to keep things simple during further discussion, I will concentrate on fairly standard examples of documentary and examination-quality photography.

In an ideal situation the photographer will have a comprehensive understanding of how an image is processed at every stage throughout the imaging chain and will be able to exert full control of every process in order to produce the best possible outcome. In practice this is difficult, if not impossible, to achieve. The digital camera market is highly competitive and manufacturers tend not to publish every detail of the processing that occurs even before the primary image is produced. Forensic photographers form a very small part of the range of users; we use cameras that are designed for the much larger market of commercial and amateur photography, which includes press, landscape, portrait, sports, weddings, and so on. One only has to browse reviews of cameras in the photography press or on-line to find examples where differing results are produced by cameras employing exactly the same imaging sensor to appreciate the point (in some ways it was the same with film: one film might have been aimed at portrait photographers, giving pleasing skin tones and relatively low contrast, while another might have been aimed at landscape photographers, giving more saturated blue skies and lush greens). Possibly the best we can hope for is for photographers to understand which image processes they can control and which processes they cannot control to enable them to make informed decisions at each stage. It is unacceptable for a photographer to neither understand nor control the processes. At best, that would lead to blind faith that the primary image produced by a camera, or the



**Figure 1.9** The digital image as an indexed two-dimensional array of values, showing pixel location.

modified image at any subsequent stage in the chain, is inherently objective and therefore ‘truer’ than one to which expert control has been applied. At worst, lack of awareness may result in images that are misleading because of the introduction of imaging artefacts.

A process may be defined as ‘a course of action or a procedure, especially a series of stages’ (*OED*), a definition well-suited here. Following the definition of the digital image, it is most useful to conceptualise the digital image as a regular, two-dimensional, mathematical matrix of discrete numbers. The position of a number within the matrix represents the geometric position of the sample (pixel) to which it relates, and the value of the numbers (‘pixel values’, or ‘digital values’) represents its intensity (brightness) and colour. If this sounds complicated, it’s not! Open an image in Photoshop; display also the *info* window; move the cursor around over the image and see what happens in the info window: the X and Y values give a pixel’s location and the R, G and B values give the pixel values (remember, a colour image is composed of three overlaid greyscale images). This is about as close to seeing the image data as we can get, but this is accessible only once the image has been saved in a format exportable from the camera and readable by Photoshop (Figure 1.9).

## 1.8 Image processing terminology

Various terms may be used to describe what, in the general sense, may be done to an image, and why. The following terms are useful in describing the various concepts of image processing, though I should note they are not universally adopted and different terms and classifications may be found. For example,

there is debate over whether *enhancement* may somehow imply an image has been materially altered, never mind *manipulation*! Once again, you may ultimately have to explain your methods in court, so choose language that you are comfortable with; language that accurately describes what you have done, and why.

- *Enhancement*: the objective improvement of visibility. Examples include improving the contrast of a finger mark and suppressing background texture or noise.
- *Restoration*: the objective removal of artefacts. Examples include: reducing image noise; correcting geometric distortion.
- *Reconstruction*: the objective compositing of a new, single, image of a scene. Examples include: combining several images of a subject that was impossible to light in one photograph.
- *Synthesis*: the production of photograph-like images from data, where the data do not originate from a digital photograph. Examples include: text annotations, computer graphics.
- *Compression*: the reduction of size of an image file.
- *Analysis*: the extraction of information. Examples include: automatic fingerprint identification systems (AFIS), automatic number plate recognition (ANPR), photogrammetry.
- *Manipulation*: it simply means ‘handling’ but is widely considered to imply subjective, or even malicious, alteration and is therefore generally avoided in the forensic context.

It is worth noting here that increasingly complex signal- and image-processing may be performed in-camera, some of which may even be ‘hard wired’ into the imaging chip, so it is getting increasingly difficult for a camera user to access image data that are truly ‘raw’. This is not the case for all cameras, however: whilst most colour cameras and DSLRs will process image files before export, alternatives are available. Scientific (often monochrome) charge-coupled device (CCD) cameras offer the best option for critical work. A good example is the Home Office’s IRIS (Integrated Rapid Imaging System) of the late 1990s, which was a finger mark imaging workstation specified with such a camera. In practice, and especially in the field, the DSLR dominates; the least-processed image file available will be the proprietary ‘raw’ format.

I will structure the following discussion in terms of the common classes of operation (the individual actions or procedures), illustrating the concepts with common examples. I will follow with some discussion about their combination into series of stages, which will involve looking again at the imaging chain, and I will end with a return to the concepts of the audit trail and best practice guidelines. I will use Photoshop to illustrate many of the operations because it is so widely used and because of its versatility. Some people consider other

applications are more suited to forensic image processing, and there may well be good arguments for the likes of MATLAB, Image Pro, V++ , and so on. On the other hand, some practitioners may not have access to specialist or expensive applications. There are some very good free applications available for download from the web, most notably (in my opinion) ImageJ, Irfanview and GIMP. Applications included as part of the suite that comes with any PC or Mac may be of some, possibly limited, use. And of course every camera and scanner manufacturer supplies proprietary software for interfacing with scanners, the management of raw files, and so on. Oh, and then there are plenty of other options such as Adobe Lightroom and Apple Aperture. If the range of possible applications is large, consider the various permutations that could be implemented! It is, therefore, practically impossible to state what should and shouldn't be used; where, and in which order; for this type of image or that. I often quote the maxim, 'it's not what you have but the way that you use it', and I reiterate my points that individuals and organisations need to establish local SOPs and responsibilities. Whatever the application, and wherever the processes are applied, all image processes share similar principles, which is where we shall start.

## 1.9 Digital image processing operations

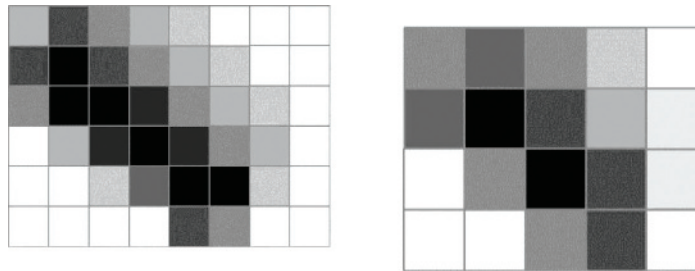
To keep things simple I will concentrate on 8-bit monochrome (greyscale) images, that is images with 256 possible grey levels. It is conventional for the minimum value, 0, to represent black and the maximum value, 255, to represent white. I will make reference to colour images and images with greater bit depths where appropriate.

### 1.9.1 Image cropping

Image cropping, if done at all, is usually performed mid-way through, or near the end of the imaging chain to remove unnecessary portions of an image. If we simply crop off a portion of an image we'll leave the remainder unaltered (Figure 1.10).



**Figure 1.10** Image cropping. An area is selected and the rest of the image is cropped out leaving the remaining portion unchanged.



**Figure 1.11** Image resampling. In this example, the image is resampled from  $8 \times 6$  pixels to  $5 \times 4$  pixels; every pixel value must be recalculated, resulting in increased blockiness and blurring.

### 1.9.2 Image resampling (resizing)

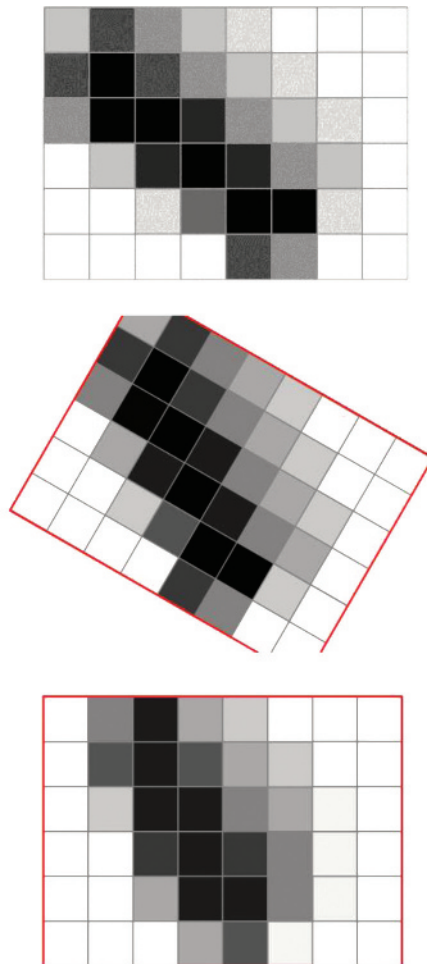
Image resampling may be performed at many stages of the imaging chain. Demosaicing involves resampling; unless an image is viewed pixel-for-pixel on a screen it will need to be resampled; printing almost always involves resampling. If we resize an image from its native dimensions then we'll be either adding or removing pixels. In the simplest case, if we reduce the image dimensions by half then the value of each 'new' pixel will be the average of the two 'old' pixels it replaces (Figure 1.11).

If we increase the image dimensions by a factor of two, the simplest method is to just double up every pixel. This method is called nearest neighbour interpolation, and the results can look blocky, or pixellated. Bilinear interpolation calculates each new, intermediate, pixel value as an average of the four (two vertical and two horizontal) surrounding original pixel values and produces smoother looking results; bicubic interpolation follows a similar procedure based on sixteen surrounding original pixel values and produces even smoother results.

When images are resized by any factor other than  $\frac{1}{2}$  or 2, similar functions to those described are applied but the maths is a little more complicated than simply averaging the values of two, four or sixteen original pixels.

### 1.9.3 Image flipping and rotation

If we simply want to produce a mirror image of an image, for example 'flipping' a footwear mark on a non-transparent transfer medium, the process is a simple transformation: each pixel will 'land' in a geometric location that is precisely in line with the initial matrix and no recalculation or interpolation will be necessary. If we use software to rotate a digital image by a multiple of  $90^\circ$  then, likewise, no recalculation or interpolation will be necessary. If, however, we rotate the image by any other angle then the pixels won't 'land' in locations consistent with the matrix and therefore every single pixel value will



**Figure 1.12** Image rotation. The image (top) is rotated clockwise by approximately  $30^\circ$  (middle) and resampled to fit the rectangular matrix (bottom image), resulting in increased blockiness and blurring.

need to be recalculated by the software (Figure 1.12). The process will involve some form of interpolation.

These processes of resampling are examples of geometric transformations. Other geometric transformations include digital zoom, scaling (stretching the image in one direction), warping, correction of lens distortion and perspective correction. All of these employ one, or a combination, of the processes described above. If multiple geometric transformation processes are applied, their effects will be cumulative. If geometric transformation processes are necessary they should be applied towards the end of any image processing sequence where possible. Any image output from a device such as a

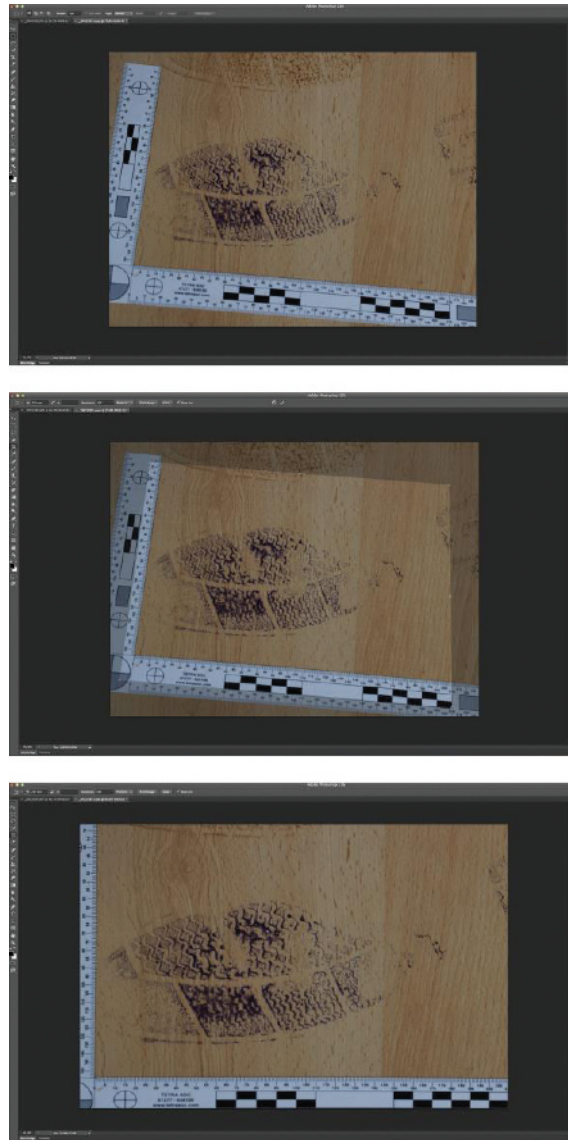


camera or scanner that differs in pixel resolution from the optical resolution of the device, will have been processed with some form of interpolation. For example, a scanner may have an optical resolution of 1200 ppi but the user may require images of 1000 ppi, an output resolution that can only be obtained by recalculating every pixel value. Photoshop's crop tool is very useful for resampling, resizing, rotating and even correcting perspective distortion, and the beauty of the crop tool is that it does this in one step.

Where geometric transformations involve resampling, any resulting pixel value that is not an integer between 0 and 255 will need rounding to the nearest value, which will introduce a small amount of noise. In addition, once the transformation has been applied and the pixel values recalculated, we can't get back to the original image simply by applying a reverse transformation because we're effectively applying two separate transformations and their effects will be cumulative. This problem can be avoided by using software that allows 'multiple un-dos' by saving previous versions of images in buffer memory *and* not saving and closing images part way through processing. I recommend exploring options afforded by Photoshop's history functions when multiple processes are used.

#### 1.9.4 Linear scales

When performing geometric transformations, whether simply rotating or resizing/resampling, or complicated distortion corrections, it is imperative to use only known control points in the image. Proper use of linear scales allows this and should give you the confidence to demonstrate, if necessary, that your application of processes has been objective and is reproducible and you have not, for example, warped the crime scene mark to match the suspect's print! Although it can be argued that linear scales are unnecessary for all documentary photos, they are certainly useful in some. Whilst someone viewing an image of, say, the exterior of a house may be able to make some assumptions about scale and perspective (is it a real house or a doll's house?) the same may not be true of more abstract documentary photos. The knife photographed against a plain, white, lab bench: is the blade 15cm or 30cm in length? A linear scale will avoid ambiguity. Linear scales are essential with images of marks. It is best practice to photograph marks from a position perpendicular to the mark so that the image magnification is uniform across the whole image, in which case only one linear scale may be necessary. But it is better to include both a horizontal and a vertical linear scale in an image to allow accurate scaling along both dimensions. In circumstances where a geometric transformation such as perspective correction will be used, it is even better to include linear scales along all four sides. The most useful scales are the specific L-shaped forensic scales, which include useful features such as accurate 90° corners, circles and crosses; ideally they should be at least as long as the area of interest; they must be legible in the image to be of use (Figure 1.13).



**Figure 1.13** Photoshop's crop tool allows resampling, resizing, rotation and perspective correction to be performed all together. Image (top) suffers from perspective distortion and is not at a scale suitable for comparison. The user may select the desired output size and resolution before placing and dragging a box (middle, highlighted section), which then becomes the output image (bottom). In this example the perspective correction is only approximate; it would have been much better to have included a second L-shaped scale to fully bound the mark, allowing reliable and accurate correction.

## 1.10 Classes of operations

### 1.10.1 Point processing

Point processes are the simplest of processes. They are processes where the output value for each pixel location depends only on the application of some mathematical function to its input value, not on the values of any other pixel location, and each output pixel is in exactly the same geometric location as its associated input pixel. The simplest cases are those where the four basic mathematical operations are applied to a single image: addition, subtraction, multiplication and division. Another approach to point processing employs the *look up table* (LUT), which, as the name suggests, is not necessarily based on any mathematical function but may simply be a list of arbitrary output values relating to possible input values, for example ‘if input pixel value = 0, output pixel value = 5; if input pixel value = 1, output pixel value = 7’ and so on; potentially any available output value can be assigned to any input value.

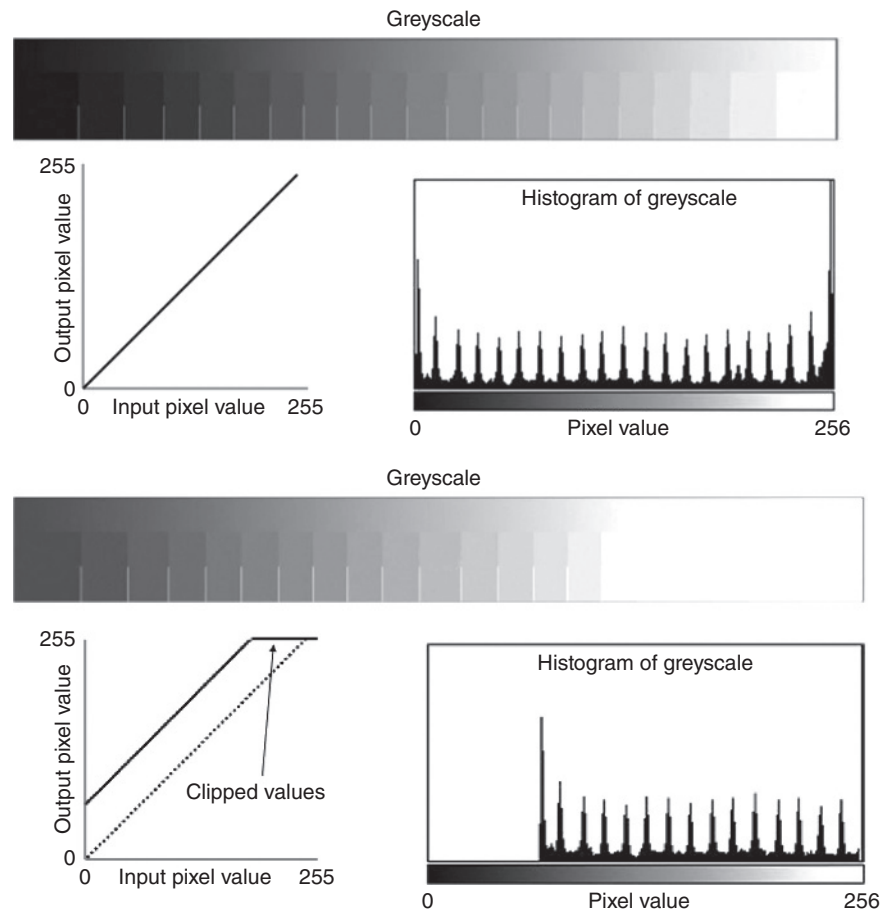
### 1.10.2 Addition

If 0 represents black and, as pixel values increase, the greys become lighter until the maximum value of 255, white, is reached, it should be straightforward to imagine that, if we were to add exactly the same value to every pixel in an image, the result would simply be a lighter image. Adding a small value, say 5, to every pixel will result in a slightly lighter image; adding a much larger value will result in a much lighter image. It’s a simple concept, but already you might spot a problem: what happens to those pixels whose values are already close to 255? If we added 10 to every pixel, then where we previously had some distinction between the very light greys of 245 and 255, all would now be 255 and we will have lost any information those levels may have contained. This is known as *clipping* in the *highlights* (Figure 1.14).

### 1.10.3 Subtraction

Conversely, if we subtract the same value from every pixel, the result will be a darker image, and if we lose the ability to discriminate between pixels whose initial values were close to 0 then, once again, we will lose information: this time the *shadows* will be clipped (Figure 1.15).

Basic brightness adjustments rely on the application of addition and subtraction. If an image is badly underexposed or overexposed there are initially unlikely to be grey levels close to 255 or 0 respectively, so the crude application of addition or subtraction may not result in clipping.

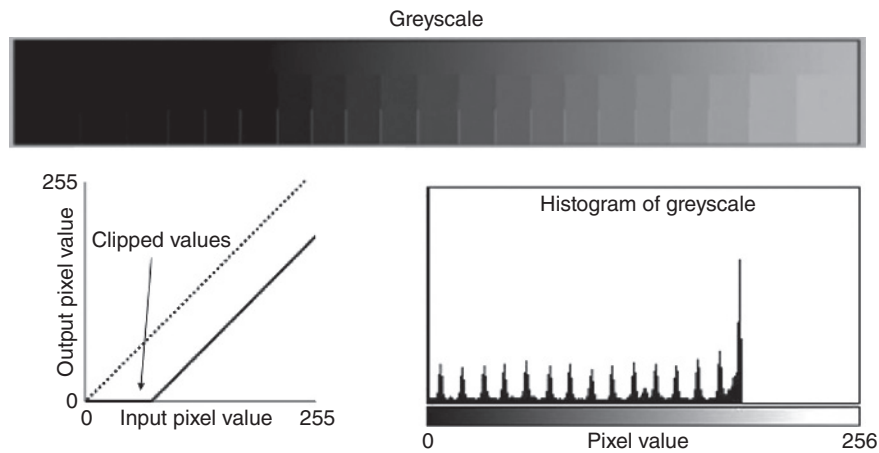


**Figure 1.14** Addition. Top: image of grey scale, graph of input pixel values versus output pixel values and associated image histogram before simple brightness adjustment. Bottom: resulting image of greyscale, graph of input pixel values versus output pixel values and associated image histogram after simple brightness adjustment (lightening). Note the loss of discrimination in the highlight region.

### 1.10.4 Multiplication and division

Division is simply multiplication by a value less than 1, so we can consider them together. If we multiply the value of every pixel by, say, 2, what will be the result?  $0 \times 2 = 0$ ;  $1 \times 2 = 2$ ;  $2 \times 2 = 4$  and so on: the result will be an image that has twice the contrast of the original.<sup>4</sup> And once we get to mid grey (128) in the original, we'll get clipped highlights in the copy. So simple

<sup>4</sup>The correct term is *gamma*, rather than *contrast*, but the latter is widely used to mean the former.



**Figure 1.15** Subtraction. Starting from the same point as in figure 1.14, top, above: resulting image of greyscale, graph of input pixel values versus output pixel values and associated image histogram after simple brightness adjustment (darkening). Note the loss of discrimination in the shadow region.

multiplication (by numbers greater than 1) gives an increase in contrast and a higher chance of clipped highlights. If we multiply every pixel value by 0.5 (the same as dividing by 2) it follows that we'll get a reduction in contrast. And we'll encounter a new problem: what happens to pixel values that initially were odd? Remember, we're dealing with binary data, so we can't have a resulting value of, say, 67.5; it will need to be rounded to 67 or 68.

In my multiplication by 2 example, the mid grey of the original becomes white in the copy; in the multiplication by 0.5 the white of the original becomes mid grey in the copy. So, as well as a change in contrast, there is a change in brightness in each case. As above, we can alter brightness by addition or subtraction so, to maintain image brightness whilst altering contrast, multiplication *and* addition or multiplication *and* subtraction are applied together. The potential for clipping remains, only now it may affect both the highlights and the shadows. The problem of rounding also remains.

I have chosen to describe these operations with reference to simple, fundamental maths for two reasons. First, the alteration of brightness and contrast in various combinations is so widely used that, to those new to the concepts of image processing, it can be quite a surprise; and even to those familiar with their common incarnations the potential power of such fundamentally simple processes can be truly astonishing: therein lies the good news! Second, the simple examples above or, more specifically, the problems they introduce – clipping and rounding – nicely illustrate further associated problems: noise and artefacts: therein lies the bad news! What would you like first, the good news or the bad news? Let's start with the bad.

### 1.10.5 The bad news: artefacts

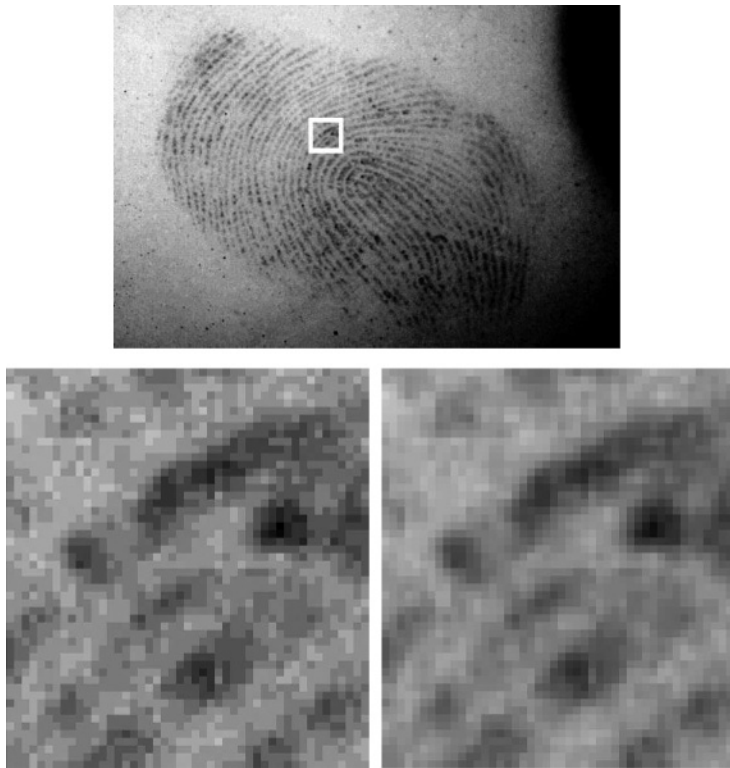
Anything introduced into an image, which results in the image not being a true representation of the scene, is an artefact. The definition includes lens flare, dust, and so on, but I'll restrict the discussion here to digital imaging artefacts. There are many ways artefacts can be introduced into digital images, including the use of long exposures, high ISO sensitivity, sharpening, compression, image rotation and so on. Once an artefact has been introduced its effect and visibility may be increased during subsequent processing, with obvious detrimental results. On the other hand, if artefacts are identified in an image, there may be a suitable process to remove or suppress them. And, as should be clear by now, the order in which a series of processes is applied can have considerable bearing on whether the problem of artefacts is worsened or lessened. By now I hope you will be wondering how it is possible to tell whether or not something, possibly unexpected, appearing in an image is an artefact, and whether or not a person processing the image will simply be removing artefacts or will be unwittingly manipulating the image. These are not trivial questions. Awareness of the appearance of artefacts, knowledge of suitable suppression techniques, skill in their application and, of course, experience will help. This applies whether you're working on images on the computer or explaining your methods in court.

### 1.10.6 The good news: versatility

White balance, colour correction, contrast, brightness, levels, curves, invert, threshold, the channel mixer, 'calculations', layers, layer blend options, high dynamic range (HDR) imaging: all of these tools employ one, or a combination of, the basic mathematical functions of addition (and subtraction) and multiplication (and division) and/or utilise LUTs. Now you should appreciate just how powerful and versatile are a few simple operations. Do, though, be aware of the potential for clipping and rounding errors and the introduction of noise and artefacts.

## 1.11 Noise reduction

One of the most common artefacts is image noise. In digital imaging we try to make a distinction between image noise and image artefacts, but it could be argued that any artefact is noise and vice versa. With forensic marks photography, we often encounter textured or patterned backgrounds, which may disrupt or hide detail in the mark, and we may consider such backgrounds to be subject noise. In practice it can be difficult, if not impossible, to distinguish between image noise and subject noise, especially if the individual examining or processing the image is not familiar with either the original mark or the characteristics of the image capture device used. When processing an image



**Figure 1.16** Noise reduction with blur filter. Top: image of finger mark, which exhibits contouring and noise as a result of extreme contrast enhancement. Bottom, left: close up of section indicated by white box. Bottom, right: same area after simple blur filter. Note: the original image was captured in JPEG format, which accounts for the poor quality. The amount of blur can be increased by either applying the same process multiple times or by increasing the size of the neighbourhood (group) to, say, five by five or seven by seven pixels.

to reduce noise, best practice should be followed, that is keep a copy of the un-processed image and keep a record of the processing.

The simplest noise reduction filter is the blur filter which, in contrast to the point processes outlined above, is a neighbourhood process. With neighbourhood processes, the output value for any pixel depends on functions applied to a group of pixels centred on the input pixel. The simplest blur filter takes a group of three pixels by three pixels and calculates their average (mean) value to produce the central output value (Figure 1.16).

A slightly different filter is the median filter. As the name suggests, rather than calculating the mean value of the neighbourhood, the median value of the neighbourhood becomes the central output value (the median value of a group of numbers is the middle value when they're rearranged in ascending order).

A third type is the Gaussian blur, which is similar in operation to the simple blur filter. The significant difference is that the Gaussian blur filter gives more weight to the central input pixel value and gradually less weight to those nearer the periphery of the neighbourhood when calculating the output pixel value. The effect of the Gaussian blur filter is closer to the effect of lens blur than other noise reduction filters.

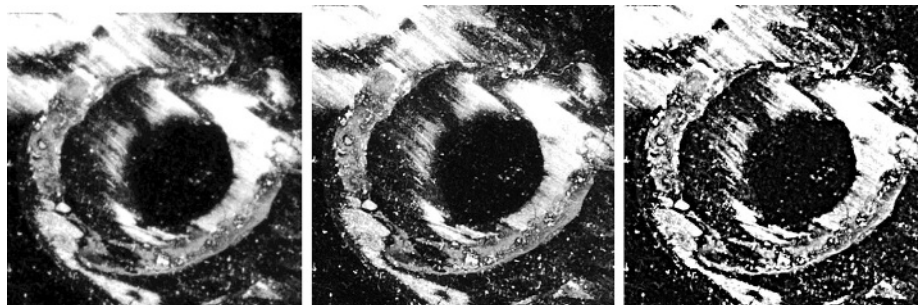
Some noise reduction filters allow the user to choose radius and threshold values. The radius value determines the size of the neighbourhood (one pixel radius equates to a three by three neighbourhood; two pixels radius to five by five and so on). The threshold value sets a minimum difference, below which an input pixel value will not be altered when calculating the output value.

More advanced noise reduction filters are available but their operation is likely to be based on one, or a combination of the three, of those described here. The general aim is to reduce noise whilst preserving detail, especially edges, but there's always a trade-off. The results of using any noise reduction filter on any image may be better or worse than the results of using another noise reduction filter. I recommend experimenting with the various filters and options at your disposal on a variety of different images and looking closely at, and comparing, the results. In practice I find myself using the Gaussian blur filter the most as its operation is more easily understood and explained than 'smart blur' type filters and it generally gives me better results than simple blur filters.

## 1.12 Sharpening filters

Sharpening filters also use neighbourhood processing operations but, in simple terms, the aim is almost the opposite to that of blur filters. The result of applying a sharpening filter is an image that appears crisper, with more prominent edges. Although fine detail may be more visible (which is why we use them) it is just an optical illusion, though an effective one. The basic sharpening filter simply increases the contrast between adjacent pixels of different value. Where there is an area of one tone, that is no difference between adjacent pixels, there will be no difference in the output image, but where there is a change in tone, for example at an edge, the contrast of the edge will be increased in the output image, hence it will appear sharper. No detail is added to the image but the detail present becomes more apparent. The basic sharpening filter does not distinguish between edges and other changes in pixel values so it will also accentuate noise. More advanced sharpening filters are available that are better at sharpening edges without increasing noise. Again, some filters allow the user to choose various values, for example amount, radius and threshold. Again, the radius value determines the size of the neighbourhood (one pixel radius equates to a three by three neighbourhood; two pixels radius to five by five and so on). The threshold value sets a minimum difference below which an input pixel value will not be altered when calculating the





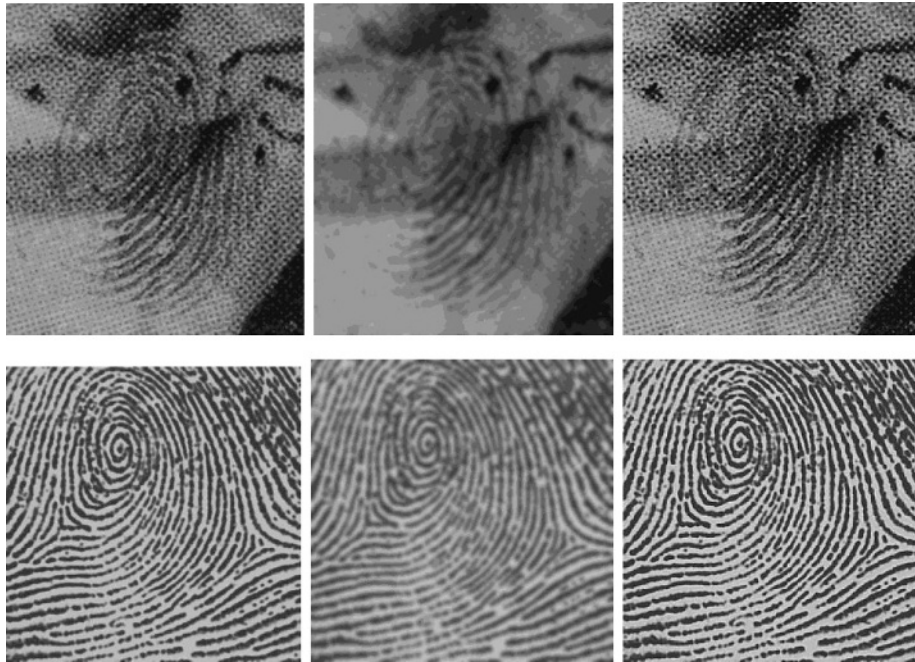
**Figure 1.17** Images of a 2 cm<sup>2</sup> section of a footwear mark. Left: before sharpening; middle: after USM, amount 100, radius 1.5, threshold 0; right, after USM, amount 200, radius 5.0, threshold 0.

output value. The amount sets the proportion by which the contrast of pixels is increased. The unsharp mask (USM) filter is such a filter, allowing a lot of control of the results, and it is the one I use the most. Again, I recommend trying the various options yourself and comparing the results (Figure 1.17).

If sharpening filters are over-applied they introduce artefacts: not only do they accentuate noise but they can add a halo effect to edges.

It is impossible to say that this filter or that filter will give the best results; results are scene dependent. For example, a small amount of blur may improve the visibility of finger mark ridges against a noisy background by effectively suppressing the appearance of the noise but at the expense of blurring some features of the finger mark ridge edges (Figure 1.18). If a sharpening filter were applied to the same original image it could make the noise more prominent and the finger mark ridges less visible. Conversely, a finger mark on a plain background is likely to become clearer with a little sharpening and less clear with a little blurring.

I should point out that as well as being scene-dependent, neighbourhood processes such as blurring and sharpening are only really effective on an image at a given resolution. Here's an example: say we use a modern DSLR to photograph a finger mark, filling the frame and using the full resolution of the camera. We might obtain an image that has an effective resolution of, say, 3000 ppi. It is rather pointless producing the visibly best image at 3000 ppi and then resampling the image down to 1000 ppi for the fingerprint bureau, because the result of resampling in this example will be to remove fine detail, which is analogous to blurring. The image should be resampled to the required resolution first and then processed to produce the visibly best image. Additionally, when processing images using neighbourhood processes, it is important to be viewing the images at a suitable resolution on screen. I always view my images at a scale of 100% and from a distance of about 50 cm – any smaller scale or any greater distance and the effect of the process may not be visible. Unfortunately there are even further complications, at both ends of the imaging chain.



**Figure 1.18** Scene dependency. Top row, left: finger mark on noisy background; middle: after a medium amount of blurring; right: after a medium amount of sharpening. Bottom, left: finger mark on plain background; middle: after a medium amount of blurring; right: after a medium amount of sharpening. The amounts of blurring and sharpening in each example are similar. Note how the visibility of finger mark ridges is improved by a different filter in each case.

Cameras generally offer image sharpening and noise reduction options in their shooting menus to be applied to images before they are saved. JPEG compression introduces both noise, in the form of blocky compression artefacts, and sharpening to enhance edges. Printer drivers and software may further process images to produce ‘better’ prints. Several times I have found that an image that looks perfect on screen looks far from perfect once printed. It must be accepted that there will be some difference in appearance between screen and print because they employ such fundamentally different technologies. The pragmatic solution involves trial and error, examination of results, tweaking of settings and gaining of experience with whatever workflow one uses. Examination of results should be suitable for the given application, for example if the final prints will be examined by a fingerprint examiner using a magnifying glass, then use a magnifying glass to examine your prints; if your final prints are general crime scene documentary photos to be viewed at arms length by an investigating officer, then why examine them with a magnifying glass?

My advice is to apply sharpening only as a final step on an otherwise ‘finished’ image, and only where it improves the visual quality of the image. This is more important with images that will undergo significant brightness, contrast

or colour adjustment through the chain, and more important with images of marks, where edge detail is so important. The reason, if it is not already obvious, is because sharpening increases contrast locally; brightness, contrast and colour adjustment further down the chain will all affect subsequent contrast, both globally and locally; most images will be subject to some form of geometric transformation at some stage in the chain; the effect of multiple processes is cumulative; and sharpening is only really effective when applied to an image at its output resolution.

My advice regarding noise reduction is not so straightforward and may even sound contradictory! In my experience many in-camera noise reduction filters do a better job during the fraction of a second it takes the camera to process the image than I have been able to do during several minutes with Photoshop. My current opinion is that the camera engineers have done an excellent job of designing noise reduction functions that perform well with their systems.

## 1.13 History log

Photoshop provides an excellent tool that helps with the audit trail: the history log. It allows a record of all that is done to the image in Photoshop to be saved, either as part of the image file or as a separate text file. It is not automatically activated; you'll need to make a few choices in the preferences menu. Go to Edit/Preferences/History and select the detailed history log option. Choose a number of stages large enough to cover all possibilities. I recommend choosing the option that saves the history to the image file's metadata, which means the record becomes part of the same file as the image data and is always associated with the image. There may be circumstances in which you wish to save the history also as a separate text file. Bear in mind the history only records anything done in Photoshop and not other processing software.

## 1.14 Layers

I recommend you investigate the functionality provided by Photoshop's layers. The basic concept of a layer is analogous to an overlay over a conventional print but layers are so much more versatile than anything physical could hope to be. I will give a couple of examples to illustrate the versatility of layers.

### 1.14.1 Adjustment layers and layer masks

Rather than performing adjustments directly on an image, if you use an adjustment layer the underlying image does not change but its appearance does, in accordance with whatever adjustment you have applied to the adjustment layer. It's similar with layer masks: rather than making a direct selection of a section of the image, a layer mask allows you to select an area to which to apply an adjustment. Advantages of using layers include: the underlying image

does not change; they can help demonstrate the important conditions of transparency and reproducibility; layers can be ‘switched’ on and off, which can aid image interpretation; they can allow processes to be undone in a way that can’t otherwise be achieved; they allow images to be saved and closed part way through processing, and later opened again, whilst retaining all of the previous advantages. Disadvantages of layers are that images can only be saved in the proprietary Photoshop file format and their use can greatly increase file sizes.

### 1.14.2 Composite images

I use layers a lot in the production of composite images, especially when photographing luminol reactions, so I will use my method as an example. Capture two images, one of the luminol reaction in otherwise total darkness and one of the scene or item (background) in normal room light. Process each image differently: process the image of the luminol reaction to best show the detail and process the background image to best show the item. Then copy the luminol image and paste it onto the background image so that the luminol image becomes the upper of two layers. Then adjust the opacity of the luminol image to show the contextual information of the background without losing any of the detail of the luminol image. If necessary the image can then be ‘flattened’, that is reduced to a single layer, so that it can be saved as either a TIFF or JPEG. Obviously, it is extremely important to ensure accurate alignment of the two layers. This can be achieved by taking great care at the time of photography not to alter the position or focusing of the camera between shots and by closely examining the composite image, switching between layers and checking the alignment of any landmarks across the entire image area. When producing composite images such as these, it is important that every image used in the composite is of exactly the same dimensions and orientations, otherwise they will not align.

The use of layers to apply adjustments and masks can be considered similar to the use of raw file conversion software: in both cases the underlying image data are not altered but the way that data are processed and displayed is modified by the choices made by the user. Layers, therefore, should offer some benefits. For example, cascading multiple processes to avoid cumulative rounding errors, which should be especially useful when dealing with images that require considerable processing, especially with 8-bit images and especially with compressed images such as JPEGs if compressed images are ever unavoidable.

## 1.15 Bit depth and dynamic range

Now seems an appropriate time to return to the subject of bit depth. I previously stated that  $2^8$ , or 256, grey levels were required in order to produce a continuous-tone image, without noticeable changes in adjacent grey levels.

Whilst that may be true, and fine for images where only small adjustments will be required later, imagine what happens if we need to greatly increase (amplify) the contrast of a faint finger mark, for example: two adjacent grey levels that were imperceptibly different may now become obviously different and the resulting image may exhibit contouring and increased noise, both image artefacts. Now imagine that instead of the original two, imperceptibly different, grey levels we had several grey levels to describe the same small transition in lightness. If we perform the same amplification to the image then the ‘top’ and ‘bottom’ grey levels will be stretched apart, just as before, but the extra levels in the middle might still allow the appearance of continuous tone and lower noise in the output image. In general terms, more grey levels equals more discrete steps (e.g. a 16-bit image can represent  $2^{16}$  or 65 536 levels) so rounding errors will be smaller, allowing multiple processes to be applied without resulting in so many image artefacts. Bit depth is related to, but is distinct from, dynamic range.

A further distinct advantage of having a higher bit depth is that it is possible to extend the effective dynamic range of an image. Dynamic range relates to the overall range of exposure that may be recorded, whereas bit depth relates to the number of separate levels that maybe coded within that range. This is one of the advantages of raw file formats, and why they allow the user to correct for white balance and small errors in exposure without losing details in highlights and shadows because of clipping.

## 1.16 File formats

DSLR cameras allow images to be saved in various file formats, most commonly JPEG (.JPG) (Joint Photographic Experts Group) and raw (the general term for proprietary raw formats although each has its own, e.g. Nikon’s .NEF and Canon’s .CR2). Other digital imaging devices, such as scanners, may allow images to be saved in a wider choice of file formats, some of which are more suited to desktop publishing and graphics applications than the photographic formats. In addition to JPEG and raw TIFF (.TIF) (Tagged Image File Format) is the most commonly used and JPEG2000 (.JP2) is useful in some situations.

## 1.17 Image compression

Image compression refers to the process of reducing file size by discarding data. *Lossless compression* means data are discarded with no loss of information, that is the pixel values of each and every pixel will be exactly the same after decompression as they were before compression. Lossless compression is achievable only at small compression ratios, typically up to 3:1. *Lossy compression* allows higher compression ratios; the higher the ratio, the more data that are discarded, with a subsequent loss of information, that is the pixel

values of every pixel will not be the same after decompression as they were before compression.

At relatively low compression ratios, JPEG and JPEG2000 will produce images that are perceptibly identical to uncompressed images. In some cases, even high compression ratios can be achieved before any visible difference is perceptible. This may be extremely useful towards the end of an imaging chain, for example to save transmission time over a wireless network. In other instances this apparent strength is a major weakness. Consider a faintly fluorescing finger mark on a disruptive background. The resulting image may have low contrast, poor colour definition, high noise content and so forth. In such a case it is precisely the initially imperceptible differences that, for example, a 12-bit raw file will record, that may later be revealed by image processing. The raw image can be enhanced to a far greater extent to reveal far more information than if the image had been saved initially as a JPEG. It is a case of not being able to recover data once they are discarded. When, and why, data are discarded; and where, and why, in the imaging chain any particular file format is chosen, are issues that should be considered.

## 1.18 Image processing at image capture

This is something that is often overlooked but, just as with the choice of file format at image capture, decisions made at the capture stage can affect the content of the image and may limit the potential for image processing further along the chain. The single biggest choice is usually, JPEG or raw? I suggest you first familiarise yourself with the effects of any choices that can be made in, for example, the camera shooting menu. Examples of settings that can affect the appearance, and therefore the content, of resultant images include (but are not limited to):

- Image size: any setting other than the 'native resolution' (the number of pixels specified on the sensor) will involve some form of resampling.
- Image quality: there is usually a choice of 'low, medium, high' or similar, often with the option of 'raw' and often with the option of raw plus low, medium or high. The choice is between saving captured images at one of three levels of JPEG compression, or raw, or both. Choose one, or a combination, suitable for the task.
- White balance: as discussed previously, it is usually best to choose a pre-set to match the lighting conditions at the time of capture.
- Colour space: sRGB is designed for on screen work; Adobe RGB is designed for more demanding work and allows a wider gamut (range) of colours to be coded.
- Colour saturation: affects the appearance of colours; in most forensic work a 'neutral' setting is most appropriate.

- **Sharpening:** affects the crispness of edges, as explained earlier. For images that will undergo minimal further processing, some sharpening can be useful, but for marks photography I recommend switching it off.
- **ISO setting:** in simple terms it is a misconception that raising the ISO raises a camera's sensitivity to light. Unlike film, which is available in different types and is removable, a camera's sensor is integral to the camera. Raising the ISO setting means having to squeeze more image signal out of an otherwise underexposed image and therefore noise will also be amplified.
- **Noise reduction (NR):** there are often several options, maybe 'off/low/high' for both 'high ISO NR' and 'long exposure NR' and different methods are used in different instances and/or in different cameras. High ISO NR aims to reduce the effects of amplifying weak image signals. A common method to reduce noise associated with long exposures is for the camera to automatically take another exposure of the same length, but without opening the shutter, to obtain a blank reference image, which is then subtracted, in-camera, from the real image.
- **'Dynamic range optimisation', 'D-lighting', or similar:** a way of producing, in-camera, an image that makes better use of the camera's dynamic range than 'standard' image capture. It can be very effective with dark or very contrasty subjects.

If shooting in any format other than raw, all user-chosen settings will be applied to the image at the point the file is first saved and cannot be undone

## 1.19 Properties of common formats

**Raw:** A 'raw' file is unprocessed or minimally processed data from the image sensor. A raw file format is proprietary to the manufacturer and the imaging system and may need to be converted to a non-proprietary format for viewing, editing, printing, and so on. Shooting in raw format allows most settings to be applied later, at the point of conversion from raw to another format. Indeed, raw files are essentially 'digital negatives': different versions can be derived from the same raw file, using different choices if desired, which is a distinct advantage. So long as the image file is not actually converted to a different file format using raw conversion software, the software does not change the actual image data, which is a further benefit of the format. Proprietary converters apply the manufacturer's decoding when opening raw files; non-proprietary converters may use a different decoding algorithm, resulting in an image with a different appearance. Similarly, no changes are made to the file when editing: editing information is carried in an associated but separate file, that is image data remain unchanged but the 'instructions' for how to display the data change. Raw files tend to have greater bit depth and greater dynamic range than other file formats.

**TIFF:** files are generally uncompressed, although the standard does allow for certain types of lossless compression. TIFF files may be either 8-bit or 16-bit. When a TIFF file is edited the image data are changed and, once saved, the changes cannot be undone.

**JPEG:** files are compressed using lossy compression, which may result in the loss of relevant information. Generally, JPEG files are 8-bit colour images, so any JPEG originating from a device with a higher bit depth will already be compressed by a reduction in dynamic range and bit depth. JPEG images may display characteristic ‘blocking’ artefacts as a result of the compression algorithm. There are 12-bit and ‘lossless’ options defined in the JPEG standard, however these not widely supported in products.

**JPEG2000:** is fundamentally different from JPEG. A different compression algorithm is employed, which has similarities to that of the Wavelet Scalar Quantisation (WSQ) file format, which was specifically designed for fingerprint images. JPEG2000 is considered suitable for some finger mark applications because it allows higher compression ratios with fewer perceptible artifacts than JPEG. JPEG2000 compression does not result in blocking artefacts.

Each file format has its strengths and weaknesses. None of the formats need necessarily be avoided but it is imperative that users are aware of the strengths and weaknesses of the common file formats. It is easily argued that in forensic contexts we should choose raw formats by default. After all, the camera captures the same initial image data whether we choose to save the image as raw or decide to throw away maybe 90% of the data, manipulate the remaining 10%, and save it as JPEG. The major drawbacks of raw relate to file handling and data storage. The IT systems of many agencies don’t support raw file formats, nor do many software applications. A pragmatic solution may be to choose the ‘high quality JPEG + raw’ quality setting, save the raw files locally and use JPEGs for networked distribution.

Bear in mind that it is possible, and easy, to open an image file of one format in an image processing application such as Photoshop and save it in a different file format: don’t assume that an image with the suffix .tif was always an uncompressed TIF! Once again, the exceptions are raw files, for reasons mentioned above.

## 1.20 Image archiving and the audit trail

Discussion of the pros and cons of the various file formats leads us on nicely to the subjects of archiving, image handling, and how to document image handling, including image processing.



### 1.20.1 Best practice and the audit trail

In the days before digital photography, things were much simpler. With black and white film we might note the development conditions; with colour film we used standardised, quality-controlled processes; all film was labelled in some way by the manufacturer and the image on the film was a physical entity. It was not necessary to keep detailed records because the processed film itself gave most of the clues one would need to ensure accurate reproduction. It is a very different story with digital photography. The proliferation of digital photographic devices and the nature of digital images mean we must pay very close attention to every detail of our digital workflow. Major considerations for forensic photography include traceability, reproducibility, authenticity and integrity.

**Traceability:** An *audit trail* should make it possible to trace any forensic photograph to a specific day, time, place; the individual who took the photograph; the camera with which the photograph was taken and many of the camera settings. The audit trail should be maintained from the time that the image is captured to the time it is transferred to the end user and is essential for evidential purposes. Digital cameras facilitate much of this by storing a lot of useful information in the metadata, such as the time at which the photo was taken, exposure settings, white balance and so on. Date and time data will only be reliable if the photographer ensures they are set correctly before photography. The audit trail should also include the method(s), conditions and equipment used to photograph the subject, including camera, lens, lighting, and the nature and order of any post-capture processing functions (including change in file format) that have been applied to the image. **Image management:** Must include assurance that the relevant data are not lost or otherwise compromised. For example, non-image data are not generally transferred to the hard copy when an image is printed.

**Reproducibility:** It should be possible for a similarly skilled practitioner to end up with similar results by following the audit trail. It should be possible to demonstrate that the working copy can be repeatably obtained from the master copy by following the audit trail and therefore accurate recording of these data is essential.

**Authenticity:** this should be established by the credentials of the organisation (police, forensic science institute), and individuals (police photographer, forensic scientist) and documented standard operating procedures (SOPs).

**Integrity:** ultimately, this is the responsibility of the individual photographer! With the best will in the world, any system is ultimately fallible to a determined, malicious individual.

Exactly how these things are achieved will vary between organisations. Some choose to have prescriptive documented SOPs, maybe allowing very little alteration of images. Some organisations may allow CSIs little control but allow specialist photographers a lot of control. Some organisations rely

heavily on written audit trails, while some rely more on electronic systems. Whatever system you operate within, be sure to follow correct procedures and do not do anything to your images that you cannot explain and defend in court. SOPs ought to be written with authority, at least in part to protect lesser-skilled practitioners so that, for example, a non-specialist CSI can stand in court and state ‘I was following procedures established by my organisation’. And then, if necessary, those who wrote the SOPs can be brought to court to explain things in more detail. There exist several publications, available on the web, which every photographer should be aware of. The prime reference is the Home Office Digital Imaging Procedure, the benchmark document, recognised around the world as best practice. It explains in detail how general workflow should be managed and documented. The essential points of the guidelines are:

- Every aspect of the process including photography, image processing, storage and archiving should be carried out by suitably trained and authorised operators.
- The audit trail must be established from the outset. This includes correctly setting the date and time on the camera (date and time data will be embedded within every image file as part of the metadata).
- After photography, transfer image files to permanent, read-only media at the earliest opportunity.<sup>5</sup>
- Protect the *original images* and work only on *working copies*. *Original images* must not be modified.
- Limit access to image files to authorised personnel only.

#### Terminology<sup>6</sup>

- *Primary Image*: digital photography is distinctly different from film photography. With the latter, the image is directly recorded onto the (removable) film, which is later processed and archived. With a digital camera the sensor remains in the camera and the digital image is first available when it is stored on a removable memory card or the computer’s hard drive if the camera is tethered to, and controlled from, a computer. There will only be *one* primary image.
- *Master Image*: the authenticated, archived bit-for-bit copy of the primary image, for example, that which is on a signature-sealed CD, filed away. The master copy must not be capable of being modified or overwritten and is kept to act as a reference image if digital evidence is ultimately presented in court.

<sup>5</sup> This is a guideline to insure integrity. In practice many organisations have moved away from the use of CDs and DVDs and instead use secure servers. There are arguments for and against each method of storage.

<sup>6</sup> These definitions are based on the Home Office Digital Image Procedure and precise definitions may differ locally.

- *Original Image*: any bit-for-bit copy of the primary image. There may be any number of copies of the original image.
- *Working Copy*: this may be an exact copy or a modified copy of the original image. Any modifications should be documented in the audit trail. An advantage of using raw files is that this is produced automatically during processing and kept in a separate associated file.

## 1.21 Printing images

Consideration needs to be given to printing digital images, where necessary. For example, very few digital printers are able to reproduce finger mark images at 500 pixels per inch at a scale of 1:1, which is the requirement for input to the UK national database. The resolution of most printers is in the range 300–400 dots per inch, so printed images will exhibit a loss in image quality. Much higher dpi figures may be quoted, particularly by inkjet printer manufacturers, partly because different printing technologies require different numbers of dots to reproduce similar detail. Tests should be conducted using a selection of representative images to determine what detail is being lost with any printer and, therefore, the printer's suitability for the task.

## 1.22 Image storage

When storing images as permanent records, other considerations become important, such as the longevity of the image file format, the longevity of the medium on which it is stored, and the means of archiving images. It is here that raw formats may show their weakness, whilst more widely adopted formats, such as JPEGs, may be continue to be widely supported. It is anticipated that stored images will be reviewed after periods of time dictated by the nature of the crime and decisions made regarding their retention or disposal. These considerations are more fully covered in the Home Office Digital Imaging Procedure and the NPIA Police Use of Digital Evidence documents.

## 1.23 Summary

Where possible, the 'best' image should be obtained at the time of capture by use of appropriate lighting and camera settings. Image processing offers many possibilities for further enhancement but it must be seen as a complement to, rather than a replacement for, the skilled control of lighting. We've only covered some of the basics in this chapter. For example, we looked at simple blur filters for background suppression. More advanced tools, such as the Fast Fourier Transform, are available. Whilst basic enhancement functions may be applied by those with a basic knowledge of image processing, advanced processing functions should only be carried out by imaging specialists who are trained and competent in their use. Local SOPs should be drafted to adequately cover the roles and responsibilities of individuals, any processes

employed, the documentation of processing, the style and format of the audit trail and so on. The Home Office's Digital Imaging Procedure is augmented by useful guidelines published by The Scientific Working Group on Imaging Technologies (SWGIT).

Many image processes are involved throughout the imaging chain, often as an automatic part of capture, display or output. Image processes often involve quite simple arithmetic operations on pixel values. Commonly, several different methods or orders of separate processes may be followed to achieve similar results. Understanding the methods can help in understanding the implications of their application and preventing unwanted quality loss. Artefacts may be produced as a result of processes, particularly when over-applied, and some processes are applied simply to correct for the artefacts produced by other processes!

I always end my discussions of image processing with the phrase, 'work backwards!', or maybe that should be 'think backwards!' The point is that because decisions made at each stage of the imaging chain have an impact on later stages, it is useful – if not essential – to consider your final output requirements BEFORE image capture (if possible): will you be able to meet your output requirements, and how will you do so? Consider what stages of the imaging chain you can control and if you can't control certain stages, what limits are imposed? And finally, beware (i.e. avoid!) capturing images which will be processed and analysed in JPEG format.