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Display Devices

05

Image output devices fall into two major categories: printing (or hardcopy) devices and display (or softcopy) devices. The image printing category includes traditional ink presses, photographic printers, and dye-sublimation, thermal, laser, and ink-jet printers — any method for depositing a passive image onto a 2D medium. Some of these devices are capable of producing transparencies, but most are used to produce reflective prints. The image display category includes traditional cathode-ray tubes (CRTs), LCD flat-panel displays, and LCD and DLP projectors — any method for the interactive display of imagery on a 2D interface. Most, but not all, display devices include an integrated light source, whereas printed output usually relies on ambient illumination. In general, hardcopy output is static and passive, and softcopy output is dynamic and active. The challenges for presenting HDR imagery within these two classes is quite different. We will look first at printing devices and then at interactive displays.

5.1 HARDCOPY DEVICES

The first image-duplication systems were hardcopy devices, going all the way back to Johann Gutenberg's invention of movable type and oil-based inks for the printing press in the fifteenth century. This was truly a digital device, requiring dextrous fingers to place the letters and designs in frames for creating master plates. (Wood block printing dating back to eighth-century China was more of an engraving transfer process.) Hand presses eventually gave way to powered flatbed cylinder presses

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in the 1800s, which are still used for many printing applications today. More significant to this discussion, the dawn of photography in the latter half of the same century opened a new horizon not only to the printing process but to what could in fact be printed.

Significantly, the chemistry of black-and-white film (and later color negative stock) has been tailored to record HDR information. As discussed in Chapter 4, the photographic printing/enlargement process is where the original range of the negative is reduced to fit the constrained range of a standard reflection print. The additional depth in the shadowed and highlighted areas of the negative permit the photographer or the processing lab to perform adjustments to the image exposure a posteriori to optimize the final image. This was the original use of the term *tone mapping*, now recognized to be so important to computer graphics rendering [131].

Figure 5.1 shows a color negative of an HDR scene next to a typical LDR print. The false color image on the right shows that the range recorded by the negative is actually quite large (nearly four orders of magnitude), and some information in the shadows is lost during standard printing. Using dodge-and-burn techniques, a skilled darkroom specialist could bring these areas out in a handmade print. By scanning the full dynamic range of the negative, one could alternatively apply one of the latest digital tone-mapping operators to compress this information in an LDR output. This fits with the idea of storing a scene-referred image and applying device-dependent tone mapping prior to final output. (See Chapters 6 through 8 on dynamic range reduction and tone-reproduction operators, for further information.)

5.1.1 THE REFLECTION PRINT

As implicitly illustrated in all the figures of this and every other book, reflective print media is inherently LDR. Two factors are responsible for this. First, the brightest pixel in a reflection print is dictated by the ambient lighting. This same ambient light illuminates the area around the print, which we can generally assume to be a medium color (midgray being 18% reflectance, but see footnote 4 in Chapter 2). Thus, even the whitest paper stock with a 90% reflectance is perhaps five times as bright as its surroundings. A typical specular highlight on a sunny day is 500 times as bright as its surroundings, and light sources can be even brighter. Would it be

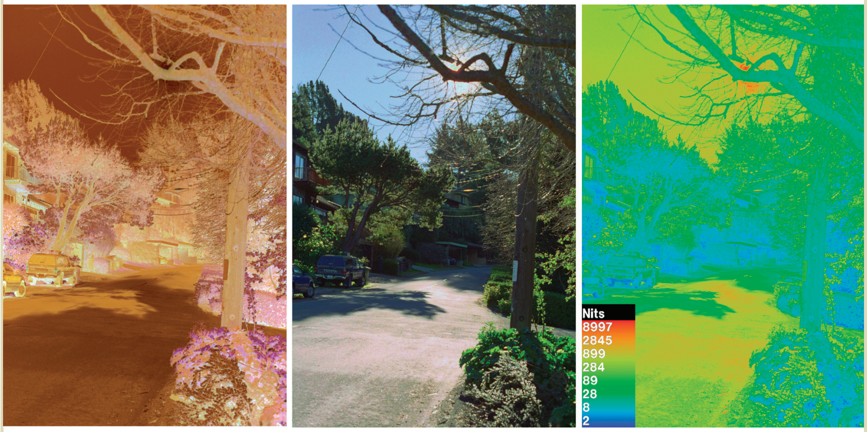

FIGURE 5.1 *A color photograph of an HDR scene. The negative shown on the left stores scene luminance with its native logarithmic response. The middle image shows an LDR print, whereas the right-hand image shows the actual range available from the negative.*

possible to represent these outstanding highlights in a reflection print? Early artists recognized this problem and added gilding to their paintings and manuscripts [40], but this would be unreliable (not to mention expensive) in a commercial print setting.

The second limitation of the contrast of reflection prints is maximum absorption, which is generally no better than 99.5% for most dyes and pigments. Even if we had a perfectly absorbing ink, the surface of the print itself reflects enough light to undermine contrast in the deep-shadow regions. Unless the illumination and background are very carefully controlled, the best contrast one can hope for in a good viewing environment is about 100:1, and it is often much less.

Figure 5.2 shows a density chart, where adjacent bars differ by roughly 11% (well above the visible difference threshold) and are spaced for optimum visibility.

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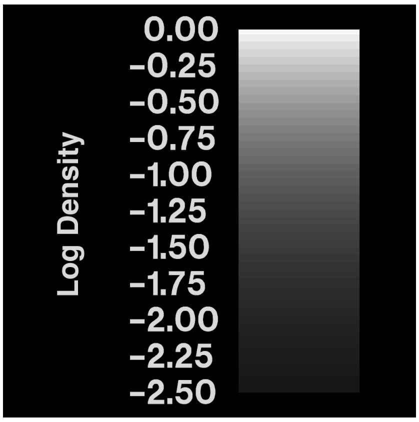

FIGURE 5.2 *A density chart, demonstrating that it is difficult to resolve differences at or below 1% reflectance* ($-2.0\ \log_{10}$ *density) in printed images.*

Even though we have given the image a black background in order to improve contrast visibility, the steps become indistinguishable well before a $\log_{10}(-2.0)$ density (1% reflectance). On an HDR display, these steps would be clearly visible all the way to the bottom of the chart. The fact that they are not demonstrates one of the inherent limitations of diffusely reflective media: LDR output.

5.1.2 TRANSPARENT MEDIA

Not all hardcopy media are reflective. Some media are transparent and are designed to be projected. The most obvious example is movie film, although 35-mm slide transparencies and overhead transparencies bear mention as well. Fundamentally, transparencies overcome the two major limitations of reflective media: ambient lighting and maximum density. Because transparencies rely on a controlled light

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source and optics for display, the ambient environment is under much tighter control. Most transparencies are viewed in a darkened room, with a dark surrounding. For maximum density, we are only limited by film chemistry and printing method as to how dark our transparency can get. Three orders of magnitude are regularly produced in practice, and there is no physical limit to the density that can be achieved.

Are slides and movies really HDR? Not really. They certainly have more dynamic range than standard reflection prints — perhaps by as much as a factor of 10. However, viewers prefer higher contrast for images with a dark surround [29], and thus manufacturers of film oblige by creating high-contrast films for projection. The sensitive dynamic range of slide transparency film is actually quite narrow — about two orders of magnitude at most. Professional photographers are well aware of this imitation. It is imperative to get the exposure and lighting exactly right, or there is no advantage in shooting transparency film. Cinematographers have a little more room to move because they go through an additional transfer step in which the exposure can be adjusted, but the final print represents only a narrow range of luminances from the original scene.

Although transparency film is not traditionally used as an HDR medium, it has this potential. Something as simple as a slide viewer with a powerful backlight could serve as a low-tech HDR display if there were some way of producing a suitable transparency for it. An example of such an approach is demonstrated in the following section.

5.1.3 HDR STILL IMAGE VIEWER

Figure 5.3 shows an HDR still-image viewer composed of three elements: a bright, uniform backlight, a pair of layered transparencies, and a set of wide-field stereo optics. The view mapping for the optics and the method of increasing dynamic range by layering transparencies are the two challenges faced [140]. The original prototype of this HDR viewer was created at the Lawrence Berkeley Laboratory in 1995 to evaluate HDR tone-mapping operators, but it has only recently been put to this task [72]. In the configuration shown, the viewer provides a nearly 120-degree field of view, a maximum luminance of 5,000 cd/m^2, and a dynamic range of over 10,000:1. It employs the Large Expanse Extra Perspective (LEEP) ARV-1 optics,

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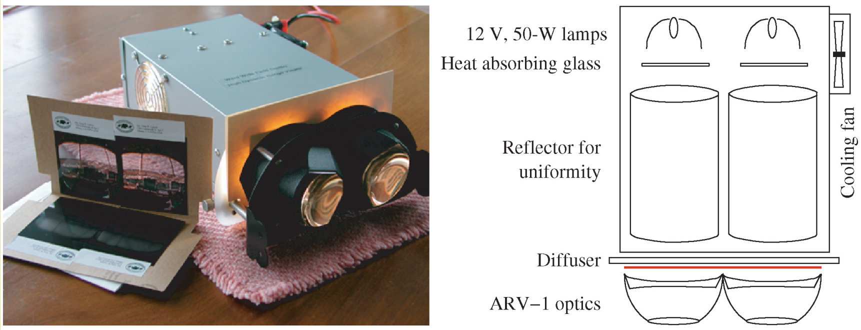

FIGURE 5.3 *An HDR viewer relying on layered film transparencies. The transparency position is shown in red on the right-hand diagram.*

which were designed by Eric Howlett and used in the original NASA virtual reality experiments [26].[1]

The LEEP ARV-1 optics use a *hemispherical fisheye projection*, wherein the distance from the center of the image is proportional to the sine of the eccentricity (i.e., the angle from the central view direction). In addition, the optics exhibit significant chromatic aberration, which will cause colored fringes at the edges of view. This was originally corrected for by a matched camera with chromatic aberration in the opposite direction, but because we seek to render our views on a computer we apply an equivalent correction during image preparation (the *Ca*( ) function, described in the following material). The image must be high resolution in order not to appear blurred in the viewer (we found a resolution of 800 dpi (2,048 × 2,048) to be the minimum). A 4-by-5 film recorder is essential in producing transparencies at this size and resolution.

1 The ARV-1/diffuser assembly was obtained from Ulrecth Figge of Boston, MA.

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A film recorder typically consists of a small slow-scan CRT with a white phosphor, which is carefully scanned three times with each of three colored filters interposed between the CRT and a film camera with a macro lens. The process is slow and the equipment is increasingly rare, making the production of high-resolution transparencies a costly proposition. Because the LEEP optics require a 2.5-by-5-inch transparency pair, we must split the job into two 4-by-5 outputs, because film cannot be printed to its borders. Furthermore, due to the difficulty of controlling transparency exposures to achieve densities whereby the film response is highly nonlinear it is necessary to create two transparency layers per eye, doubling the cost again.[2]

Figure 5.4 shows the method for splitting a single HDR image into two transparency layers, which will later be mounted one atop the other in the viewer. Because the same image separation is needed to drive the HDR softcopy displays (described in the next section), we explain the process here. The incoming image must be normalized such that the maximum pixel value is no greater than 1.0 (i.e., maximum transmission). First, the pixels in the original image are blurred, which circumvents the otherwise insurmountable problems of misregistration and parallax between the two layers. We use a Gaussian blur function to reduce the apparent resolution of the back image to roughly 32×32, although we have found that resolutions as low as 16×16 will work. We then take the square root to cut the original dynamic range of our back layer in half. This is the key to getting an HDR result, in that standard film recorders cannot handle more than an 8-bit/primary input file.

By subsequently dividing this back layer into the original, we obtain the front image, which is passed through the $Ca()$ function to correct for the aforementioned chromatic aberration. The $Ca()$ function simply makes the red channel in the image 1.5% larger than the blue, with green halfway between. By construction, the front layer will have enhanced edges that precisely compensate for the blurred back layer, as explained in material following. Because densities add in layered transparencies (i.e., transmittances multiply), the original HDR view is reproduced almost perfectly.

Figure 5.5 demonstrates the recombination of image layers. By dividing our original image (reproduced on the right) by the blurred back image (shown on the left),

2 The cost per image is about $50 U.S., and four images are required per view.

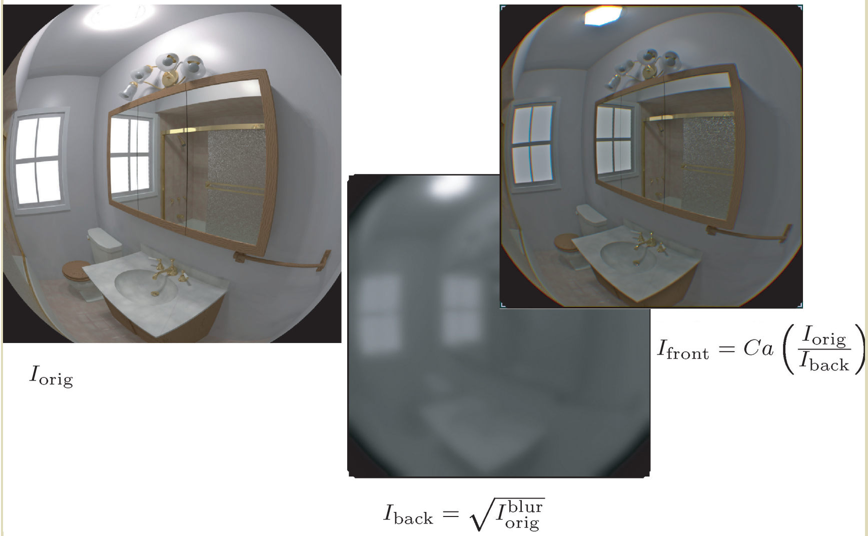

FIGURE 5.4 *The process whereby the original fisheye image for one eye is split into two transparency layers, which when combined in the HDR viewer will reproduce the original luminances.*

we obtain by construction the foreground image necessary to recover the original. As long as the dynamic range of the foreground transparency is not exceeded, this result is guaranteed. This method is called dual modulation.

However, even if the dynamic range of the front image is exceeded, the limitations of the human visual system help mask the artifacts. At the point where we overtax the capacity of the front image, a contrast on the order of 100:1, scattering in the eye makes it impossible to distinguish sharp boundaries. Figure 5.6 (left) shows the approximate point spread function of the human eye. Figure 5.6 (right) shows the desired and the reproduced image for ??? device such as this. Due to the blurring of the back image, there is some spillover at the edges of this high-contrast

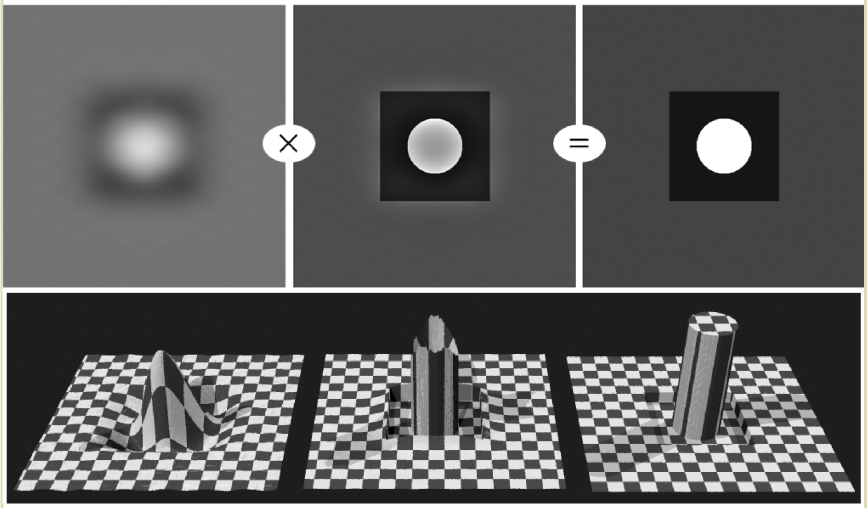

FIGURE 5.5 *Demonstration of how a blurred background image recombines with a carefully constructed foreground image to reproduce the original.*

boundary. However, due to scattering in the eye, the human observer cannot see it. The bright central region effectively masks this error as an even greater amount of light spills over on the retina.

The HDR transparency viewer described is an interesting device, as it demonstrates the feasibility of splitting the image into two layers that together produce an HDR view. However, its limitation to still imagery for a single observer makes it impractical for anything outside the laboratory. Even so, the same principles we have introduced here apply equally to HDR softcopy displays, particularly those developed by Sunnybrook Technologies (discussed in the following section).

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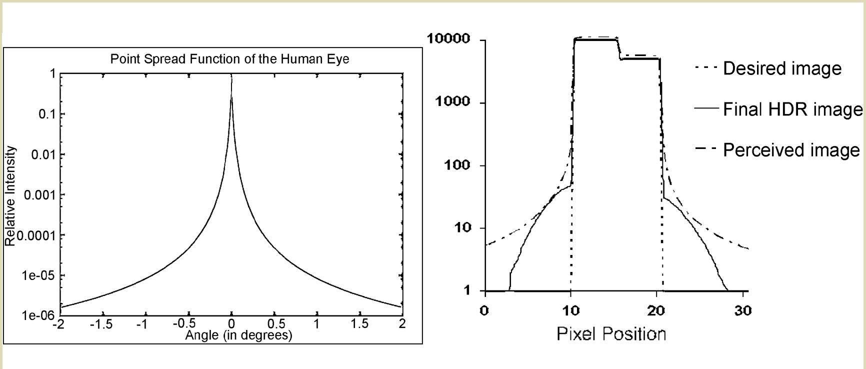

FIGURE 5.6 *The point spread function of the human eye (left) and its effect on the visibility of spillover at high-contrast boundaries in a dual modulator's output (right).*

5.2 SOFTCOPY DEVICES

For the purposes of discussion, we define a *softcopy* device as an electronic device that can be used in an interactive setting. This excludes movie film projectors that display in real time something whose preparation is far from it. This section therefore focuses on the two most popular display technologies before we venture into some of the newer and less well-known devices.

5.2.1 CATHODE-RAY TUBES AND LIQUID CRYSTAL DISPLAYS

The first softcopy device was the cathode-ray tube (CRT), invented by German physicist Karl Ferdinand Braun in 1897. A CRT is a vacuum tube configured to dynamically control the aim, intensity, and focus of an electron beam, which strikes a phosphor-coated surface that converts the energy into photons. By depositing red, green, and blue phosphors in a tight matrix and scanning the display surface at 30 Hz or more, the eye can be fooled into believing it sees a continuous 2D

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color image. Through these and other refinements, the CRT has held its place as the leading softcopy display device over 100 years later, making it the most successful and longest-lived electronics technology ever developed.[3] Only in the past decade has the liquid crystal display (LCD) begun to supplant a substantial portion of traditionally CRT-based applications, and LCDs currently dominate today's portable electronics market.

A good part of the success of the CRT is its inherent simplicity, although a century of tinkering has brought many variations and tens of thousands of patents to the basic technology. By tracing an electron beam (usually a triple beam for RGB) across a fixed phosphor-coated-matrix, the actual number of electronic connections in a CRT is kept to a minimum. By comparison, an active-matrix LCD has an associated circuit deposited on the glass by each pixel, which holds the current color and drives the liquid crystal. This adds up to millions of components on a single LCD display, with commensurate manufacturing costs and challenges (up to 40% of displays off the assembly line are discarded due to "stuck" pixels and other problems). Even today there are only a handful of electronics makers capable of fabricating large active-matrix LCD screens, which other manufacturers then assemble into final products.

Figure 5.7 compares the anatomy of a CRT pixel to that of an LCD. In a CRT, each pixel is scanned once per frame, and the phosphor's gradual decay (coupled with the brain's integration of flashed illumination faster than 60 Hz) makes the pixel appear as though it were constant. In an active-matrix LCD, the pixel is held constant by the combination of a capacitor and a thin-film transistor (TFT), which acts as a short-term memory circuit between refreshes. As we mentioned, this circuitry adds to the cost and complexity of the LCD relative to the CRT, although these costs will reach parity soon. When one considers the end-to-end cost of CRTs, it is seen that their additional bulk and weight create shipping, handling, and disposal difficulties far beyond those of LCDs (and most other replacement technologies). LCDs have already surpassed CRT sales in the computer display market and are poised to take over the television market next.

Regarding dynamic range, CRTs and LCDs have some important differences. The fundamental constraint for CRTs is their maximum brightness, which is limited

3 Technically, the battery has been in use longer, but the battery does not fit within the standard definition of "electronics," which is the behavior of free electrons in vacuum, gasses, and semiconductors.

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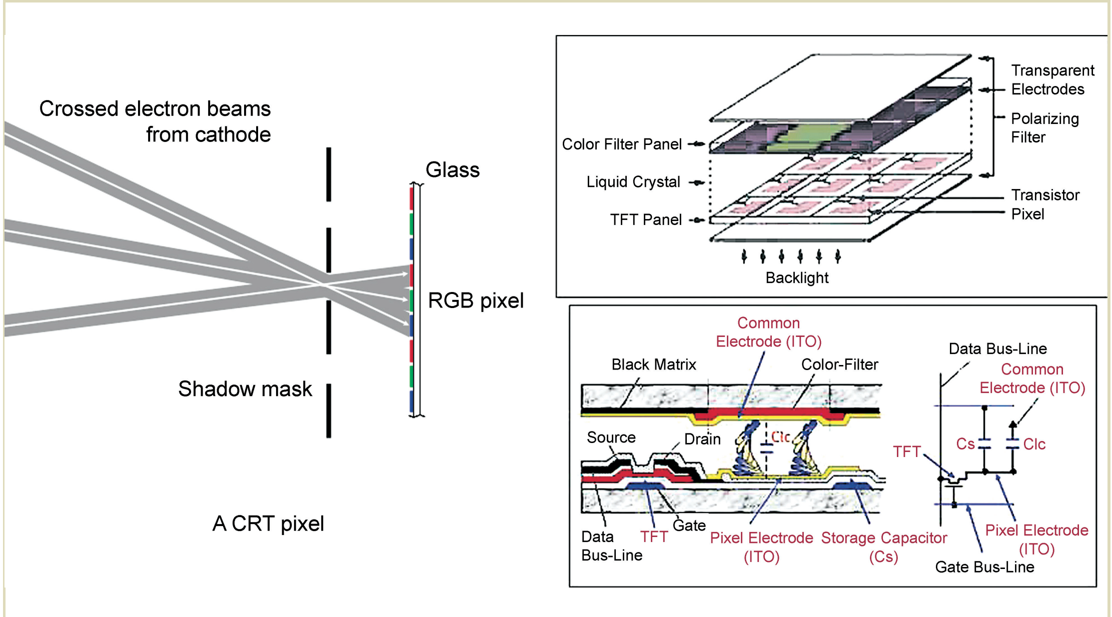

FIGURE 5.7 *A CRT's pixel compared to that of a liquid crystal display (right). (Note to editor: need to ask permission of AVDeals.com for right image or find a better one.)*

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by the amount of energy we can safely deposit on a phosphorescent pixel without damaging it or generating unsafe quantities of X-ray radiation. By comparison, there is no fundamental limit to the amount of light one can pass through an LCD screen, and in fact the LCD itself need not change (only the backlight source). However, CRTs have one advantage over standard LCDs, which is that a CRT pixel can be switched off completely, whereas an LCD pixel will always leak some small but significant quantity of light (limiting its effective dynamic range). Technically, a CRT display has a very high dynamic range, but it is not useful to us because the range is all at the low end, where we cannot see it under normal viewing conditions. Conversely, the LCD can achieve high brightness, but with a limited dynamic range.

The only way to improve the dynamic range of an LCD is to modulate the backlight. Because most LCD backlights are uniform sources, one can only alter the overall output of the display in such a configuration. Of course, uniform modulation would not improve the dynamic range for a single frame or image, but over a sequence of frames one could achieve any dynamic range one desires. Indeed, some manufacturers appear to have implemented such an idea, and there is even a patent on it. However, having a video get drastically brighter and dimmer over time does not fulfill the need for additional dynamic range within a single frame. This gives rise to alternative technologies for providing local LCD backlight modulation. Two such approaches are described in the following.

5.2.2 SUNNYBROOK TECHNOLOGIES' HDR DISPLAYS

Sunnybrook Technologies of Vancouver, Canada (*www.sunnybrooktech.com*), has explored both projector-based and light-emitting diode (LED)-based backlight modulators in its HDR display systems [114,115]. Similar to the concept presented in Section 5.1.3, a low-resolution modulator is coupled with a compensated high-resolution front image (the LCD) to provide an HDR display free of pixel registration problems. The principal difference is that the Sunnybrook displays are dynamic and can show video at real-time rates. As these are otherwise conventionally configured displays, they have the external appearance of a standard monitor and unlike the original 2B transparency viewer are not restricted to a single observer.

A diagram of Sunnybrook's projector-based display is shown in Figure 5.8. The original prototype employed an LCD-based projector, and the later models use a

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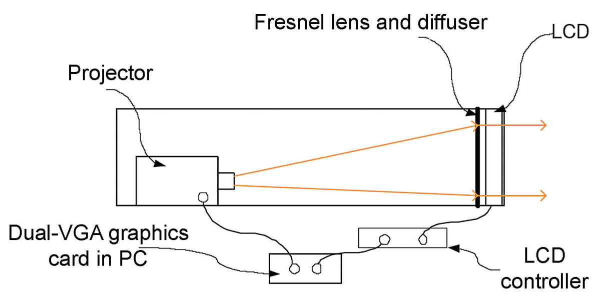

FIGURE 5.8 *Sunnybrook Technologies' projector-based display [114].*

modified black-and-white DLP projector (see Section 5.2.3). All units employ a high-resolution LCD panel as the final view portion of their display. By using the projector to effectively modulate the backlight of the front LCD, they are able to present images with a dynamic range in excess of 50,000:1. Depending on the exact configuration, the maximum luminance can be up to 2,700 cd/m^2 for a single observer — at least 8 times brighter than today's standard LCD displays, and 15 times brighter than the best CRTs.

However, there are a number of important drawbacks to using a projector as a backlight. First, the optical path required by the projector means that the display itself is large — about 100 cm in depth. Custom optics or some mirror arrangement could reduce this dimension, but similar to a projection-based television it will never be as small as a CRT display of similar display area and resolution. Second, the incorporation of a Fresnel lens to boost brightness and improve uniformity incurs a cost in terms of light falloff at wider viewing angles.[4] Finally, the light source for the projector must be extremely bright in order to support a high maximum

4 The Fresnel lens is a thick sheet of acrylic, embossed with a circular pattern that simulates a much thicker lens. This is preferred in applications where cost and weight are more important than image quality. Because the rear image is low resolution and the Fresnel lens is followed by a diffuser, this arrangement has no impact on image quality.

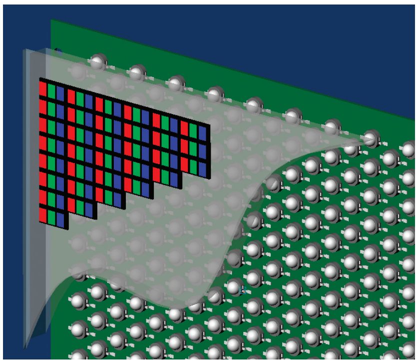

FIGURE 5.9 *Sunnybrook Technologies' LED-based display [114].*

luminance through two modulators, and this translates to a high (and unvarying) power consumption with associated heat dissipation issues.

In consideration of these problems, Sunnybrook subsequently developed the LED-based display shown in Figure 5.9. Replacing the projector as a backlight, this newer display employs a low-resolution honeycomb (hexagonal) array of white LEDs mounted directly behind the LCD's diffuser. No Fresnel lens is needed to compensate for projector beam spread, and because the LEDs are individually powered consumption is no longer constant but is directly related to display output. Because most HDR images will have only a fraction of very bright pixels (less than 10%), the average power consumption of this device is on par with a standard CRT display. Furthermore, because the LED array is inherently low resolution, Sunnybrook is able to encode the data needed in the first scan line of the incoming video signal, rather than providing a separate video feed as required by the projector-based display.

The LED-based display has a higher maximum output (8,500 cd/m^2), with a similar dynamic range. The chief drawback of this new design is the current cost of the high-output white LEDs used in the backlight. Fortunately, the cost of these relatively new components is dropping rapidly as the market ramps up, and the price point is expected to be in the reasonable range by the time the display is ready for market. In contrast, the cost of high-output digital projectors has largely leveled off, and the price of the projector-based display will always be greater than the projector inside it.

5.2.3 OTHER DISPLAY TECHNOLOGIES

Most other work on HDR display technology is happening in the nascent field of *digital cinema*, whereby major studios and theater chains are hoping to replace their current film-based equipment with electronic alternatives. Already, over a hundred theaters in the United States have installed digital projection systems. Most of these projectors use the Texas Instruments Digital Light Processing (DLP) system, based on their patented Digital Micromirror Device (DMD).

These devices were the first large-scale commercial application of microelectromechanical systems (MEMS). A DMD chip consists of a small high-resolution array of electrically-controlled two-position mirrors, a subsection of which is pictured in Figure 5.10. Each mirror is individually controlled and held in position by an underlying circuit, similar to that of an active-matrix LCD. The chief difference is that rather than transmitting a percentage of the light and absorbing the rest, the DMD reflects about 85% of the incident radiation, but in a controlled way that permits the desired fraction to continue onto the screen and the rest to be deflected by 10 to 12 degrees onto an absorbing baffle. Thus, the DMD can handle much greater light intensities without risk of overheating or light-associated damage, despite its small area. Because it is inherently a binary device, time modulation is used to control the average output at each pixel. For example, a micromirror at 25% output is in the "off" orientation 75% of the time. Color is achieved either by ganging three chips through a beam splitter or by using a flying color wheel whereby red, green, and blue images are presented sequentially to the screen. This is all made possible by the fast switching times of the micromirror elements (about 15 microseconds).

In principle, there is no reason to believe that DMD technology would not enable direct HDR display. In practice, however, the dynamic range is limited by the amount of light scattering from mirror edges, hinges, and the spacing required for clearance. Hence, the actual, delivered dynamic range of commercial DLP chips is on the order

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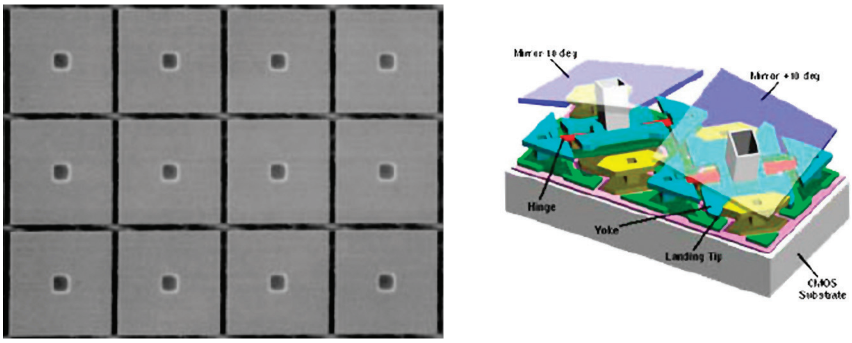

FIGURE 5.10 *Twelve pixels on a Texas Instruments micromirror (DMD) array, and a section detailing two neighboring pixels. Each square mirror is 16 microns on a side, and DMD resolutions up to 1,024 × 768 are available.*

of 500:1, despite some manufacturers' more optimistic claims (usually based on "all-on" versus "all-off" measurements). With time, we can hope that this ratio will continue to improve, and Texas Instruments, latest DDR DMD chips employ a dark inner coating to minimize unwanted reflections. However, there appear to be practical limits to how far DMD technology can go.

An even more promising projection technology, which has been on the horizon for some years now, is Silicon Light Machines' grating light valve (GLV), shown in Figure 5.11. This MEMS device provides rapid and efficient control of laser reflection via a tiny, controllable diffraction grating. Similar to the DMD in concept, the GLV uses smaller-scale elements (a few microns wide), with displacements smaller than the wavelength of visible light. This yields rapid, continuous control (about 0.1 microseconds from 0 to 100%) between mirror and diffraction grating in what is inherently an analog device. Although no commercial displays are yet available using this technology, the design trend is toward vertical (column) arrays, swept across the

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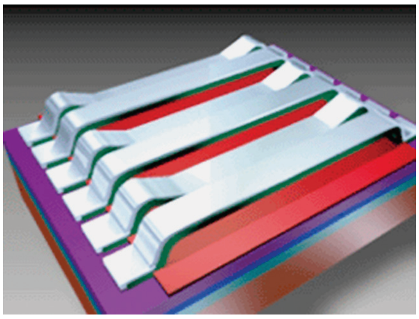

FIGURE 5.11 *Silicon Light Machines' micrograting (GLV) pixel. Each ribbon is about 5 microns wide.*

screen to make a complete image using laser scanning or similar techniques [14]. It is difficult to predict what to expect of these devices in terms of dynamic range, but there are several parameters available for tuning and few apparent limitations to the ultimate control that may be achieved [97]. Operating at wavelength scales provides new opportunities for control efficiency that larger devices such as LCDs and DMDs cannot easily match.

Finally, the HDR potential of LED-based displays bears mentioning. An active matrix of LEDs would solve nearly all of the problems discussed so far. Outputs could go down to zero at each pixel, potentially generous maximum outputs would be possible, and cross-talk between pixels would be negligible.

Unfortunately, the technical barriers involved in constructing such a display are formidable. The large-scale microcircuit fabrication requirements are similar to those of LCD panels, except that the power levels are greater by several orders of magnitude. In addition, the color and output variation in current LED manufacturing is high, causing makers to rely on "binning" individual LEDs into groups for consistency. It is difficult to see how binning could be used in the manufacture of

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a display with over a million such devices, but manufacturing methods continue to improve, and we expect that production will be more consistent in a few years.

However, heat dissipation is critical, as LED output is very sensitive to temperature and efficacies are too low at present for a practical large HDR display. So far, only Kodak and Sony have marketed products using organic light-emitting diode (OLED) displays, and these are comparatively small, low-output devices.[5] Nevertheless, because LED displays are inherently HDR, the potential is there.

5 Kodak's NUVUE AM550L device is 44 × 33 mm^2 at 520 × 220 resolution, with a 120-cd/m^2 maximum output level.