Chapter 6

Security Papers: Trust but Verify

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6.1. INTRODUCTION: PURPOSES OF SECURITY PAPER PRODUCTS

Security paper products are all around us in the form of currency, lottery tickets, passports, stamps, and check forms, among others [Martin 2014]. A key attribute of such products is that the accepted value of the sheet or stub can greatly exceed the value of the materials and the effort involved in manufacture. That would seem to be an ideal product line for a paper manufacturer! However, no other paper product is so routinely abused through folding, crumpling, soiling, and even occasional laundering [Bureau of Engraving and Printing 2006]. Also, the tonnages generally are not large compared with some other grades of paper. Because banknotes present some of the greatest challenges for the manufacturer, such products will be emphasized in this chapter.

In the United States the idea of security paper goes back to the founding of our nation. Benjamin Franklin [1780], who was a printer by trade, promoted the use of paper as an ideal medium for promissory notes and bills of exchange. The idea of paper money seems to have been introduced to the European world by Marco Polo, who in the 13th century described the “flying currency” of China [Der Papiermacher 1994]. The Bank of England started printing banknotes in 1695 [Der Papiermacher 1994]. Richardson [1833] advocated for the use of paper money, stating its advantages relative to heavy and space-constrained metal coins. Rossman [1928] described the developing field of “safety papers.”

Even in this era of online transactions, credit cards, smartphone payments, and bitcoins, people still like to use “real money” [Nishibe 2016]. The images on money can evoke pride and confidence in one’s government [Prill et al. 2015; Rogoff 2015]. A banknote offers the user the advantages of access, anonymity, convenience, and acceptability [Bureau of Engraving and Printing 2006; National Research Council 2007]. At the same time, as will be described in this chapter, the paper medium offers multiple opportunities of deterrence and detection of forgery [Bureau of Engraving and Printing 2006; National Research Council 2007].

6.2. WHY PAPER AS A MEDIUM FOR SECURE DOCUMENTS

6.2.1. Inherent Features of Paper

The manufacturer of security paper products is in a continuous campaign to demonstrate that effective countermeasures to counterfeiting are best incorporated into a paper document either at the time of forming the sheet or afterward during production-scale printing operations [Lockie 1997]. The idea is that the economy of scale of centralized production of security paper can provide means of incorporating multiple recognizable features that would be beyond the means of typical forgers. Key features that the producers of security paper aim for (when considering the forming of the paper, its printing, and other modifications) include recognizability, relatively low cost, ease of incorporating forgery-resistant features, and opportunities for forensic analysis.
6.2.2. Recognizability

The quality of the artwork, faces especially, is often a key trigger for members of the general public to become legitimately suspicious of whether a banknote is genuine [Bureau of Engraving and Printing 2006]. Subtle differences related to background color, multicolor aspects, and texture also appear to be prominent clues for the nonprofessional handler of currency to detect a fake [National Research Council 2007]. The first indication of trouble often is when a security document looks suspicious or feels suspicious.

An experienced cashier will frequently use backlighting to check various aspects of banknotes, taking advantage of the translucent nature of paper. Some features that are apparent in transmitted light cannot be copied using typical copying equipment, which generally relies on reflected light [National Research Council 2006].

6.2.3. Relatively Low Cost

Although the face value of a banknote or check may be very high, the cost of producing the object needs to be low. A high rate of production needs to be paired with high precision and reliability of adhering to specifications [Bureau of Engraving and Printing 2006; National Research Council 2007]. As will become apparent from examples discussed in this chapter, security features adopted for use by governments and organizations tend to be those that offer the best ratio of recognizability and verifiability to cost.

6.2.4. Forensic Opportunities for Verification

Because of details in papermaking equipment, procedures, and sourcing of materials, any paper product can be said to have a “personality” that could be verified by analysis in a high-tech laboratory. For instance, the wiremark of a paper sheet can be detected and compared with that of a genuine specimen [Helle 1988]. Also, it has been proposed to employ analysis of fiber directionality to distinguish between true and bogus paper in banknotes [Takalo et al. 2014]. Although fibers in paper typically show a preferred orientation in the direction of manufacture, the extent of this attribute depends on details of the paper-forming equipment and operational settings. The three-dimensional nature of paper can be expected to provide further opportunities for verification, especially when state-of-the-art security features are incorporated [National Research Council 2007]. Detailed chemical analysis, such as mass spectrometry [Watling 1999], offer means to determine whether a suspect item has the correct background composition, even if soiled with various contaminants.

6.3. CHALLENGES FACING SECURITY PAPER PRODUCTS

6.3.1. Modern Counterfeiting

In previous generations, skilled craftspeople were generally the most successful producers in “passable” forged items. That situation has changed with the widespread availability and increasing fidelity of color copiers [National Research Council 1993, 2007]. Although the results of such copying tend to be quickly detected by banks, experienced cashiers, and vending machines [Bureau of Engraving and Printing 2006;
National Research Council 2007], the required level of skill and effort to be able to produce a casually passable banknote has decreased.

Forgery efforts by hostile states can offer much greater challenges in terms of detection and verification [Bureau of Engraving and Printing 2006]. Such entities may have the incentive and means to set up the needed papermaking and printing operations to basically mimic what is done by the legitimate producer. Governments review and occasionally update their security features and other aspects to combat such potential threats and to make it easier to confirm counterfeits once suspicions are raised.

6.3.2. Durability

Paper money, in particular, needs to have a high resistance to tearing, even when wetted [National Research Council 2007; Kyrychok et al. 2013]. Extensive testing went into selection of the types of fibers, pulping treatments, chemical additives, and surface sizing treatments that continue to be used for U.S. currency [Shaw and Bicking 1929; Carson and Shaw 1946; Bureau of Engraving and Printing 2006].

6.3.3. Ideal Attributes of Counterfeit Prevention Features

To deter and detect counterfeiting, a security paper item can contain a variety of features either within it or printed onto it. Teams of experts have weighed a wide variety of such features to anticipate which of them are the most promising and cost-effective [National Research Council 1993; Bureau of Engraving and Printing 2006]. In general terms, an ideal forgery-resistant feature ought to be difficult to duplicate, easily recognized by members of the public, durable, and easy to manufacture at low cost, as well as being pleasing and safe [National Research Council 1993]. In addition, an effective security feature should facilitate authentication in cases where a document raises suspicion or fails a first-line machine detection system, such as a bill-counting machine at a bank. Figure 6.1 provides a listing of some key aspects of papermaking and printing that will be considered in this review article as ways to discourage, detect, or confirm forgeries.

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6.4. DEFENSES AGAINST COUNTERFEITING

Before considering aspects of manufacture of security paper, with an emphasis on currency, this section will review, in general terms, the methods that have been most successful in recent years in the detection and confirmation of forgeries.

6.4.1. Vigilant Cashiers

Experienced cashiers spot forgeries, from time to time, based on general appearance. They also use backlighting to inspect such features as watermarks and plastic strips [National Research Council 1993]. Because most modern printing paper, but not currency paper, contains starch, cashiers and tellers frequently use a starch-detecting felt-tip device (like a marker) to check banknotes [Pifferi 1997; Bureau of Engraving and Printing 2006].
6.4.2. Machine Readers

Most of the clues used by tellers and cashiers are ignored by high-speed mechanical devices, which often rely heavily on fluorescent effects, infrared-ink effects, and magnetic effects to judge presumably true from false items [National Research Council 2007].

6.4.3. Forensic Analysis

When suspicion has been raised, how does one completely rule out the possibility that one has in hand a counterfeit item? As a first stage, one inspects some of the many security features that may be present, a topic that will be considered toward the end of this chapter. Recently Potolinca et al. [2017] showed that detailed chemical analysis can be used reliably to determine whether the base paper comes from the same source as the genuine article.

6.4.4. Emerging Defenses Against Counterfeiting

Computer technology, although often regarded as a competitor to paper, can be expected to play an increasing role in plagiarism detection. For example, Takeda and Omatu [1995] and Frosini et al. [1996] showed that a neural net algorithm was able to efficiently detect and verify false banknotes from various countries. Similar work by Sargano et al. [2014] successfully judged Pakistani currency based on color-scanning information alone. Another approach, taking advantage of the increasing power and speed of networked computers, would be to check the serial numbers of scanned banknotes; large batches of forged banknotes often have repetition of the same serial number [National Research Council 1993].

6.5. BASE-STOCK PRODUCTION FOR SECURITY PAPERS

Before one can seriously consider incorporation of security features, it is first necessary to meet the physical property requirements and other specification of the paper itself. This can involve selection of the fiber type or types, fiber processing conditions, and various chemical treatments.

6.5.1. Fiber Selection

Tests carried out by Shaw and Bicking [1929] showed that a mixture of cotton and linen fibers, after cooking in alkali, yielded suitably tough paper for use as currency. The linen (flax) provided greater bondability, whereas the cotton content contributed to better printability. A ratio of 3:1 cotton:linen has been stated [Bureau of Engraving and Printing 2006]. It is advisable to use the strongest fibers available, given the high degree of wear and abuse to which currency paper is subjected [Koeze 1979; Kyrychok et al. 2013].

As depicted in Fig. 6.2, cotton fibers are available in two classes, the longer of which are generally 22–33 mm in length (the fibers or “lint”) and the shorter of which are generally 12–15 mm in length (the “linters”), all with diameters of up to approximately 20 μm. The linters are generally regarded as more suitable for papermaking because of their favorable length. Flax fibers, which are constructed of multiple bast cells fused together, have typical length of 10–120 mm and widths of 15–30 μm [Müssig and
Mechanical refining, depending on how vigorously it is applied, can be expected to shorten the fibers (especially the flax) and fibrillate the surfaces. Both types of fiber have much less lumen space and denser structure than wood-derived fibers [Wakelyn et al. 2006].

Depending on the application, it is reasonable to expect that many other kinds of security paper products can be prepared using materials that are currently more typically used in the production of printing papers (i.e., bleached kraft wood pulps, calcium carbonate as a filler for opacity and cost reduction, and surface sizing with starch) [Neimo 1999].

6.5.2. Avoidance of Certain Components

Because of how the commonly used forgery-detection strategies work, certain components are avoided in the production of U.S. currency paper, most notably starch, calcium carbonate, and fluorescent whitening agents (FWAs) [National Research Council 2007]. This is the basis of the “starch pen” test [Bureau of Engraving and Printing 2006] mentioned earlier. An alternative approach, although apparently not as much used, involves a pH marking pen [Blackledge and Gernandt 1993], taking advantage of the fact that almost all copy paper available in the United States is produced on paper having an extract pH of approximately 8, whereas currency paper is processed under acidic conditions. This kind of test is illustrated schematically in Fig. 6.3. Copy papers also routinely employ stilbene-type FWAs, which absorb ultraviolet (UV) light and re-emit energy in the blue region [Crouse and Snow 1981]. If such FWAs were applied to currency paper, they would interfere with other fluorescent effects associated with security features, as described later. It should be noted that currency often becomes contaminated with FWA due to laundering or due to contact with clothing; such contamination can happen due to the addition of FWAs to washing machine detergents [National Research Council 1993].

6.5.3. Papermaking Additives

Papermaking can be viewed as a process of preparing an aqueous mixture of cellulosic fibers and then forming the material into a thin mat by drainage of the water through a screen. The process is completed by pressing (to densify the sheet and increase the solids content to about 50%) and drying. Figure 6.4 is a sketch of one kind of typical paper machine system that can be used for preparing specialty paper products. The system shown comprises a cylinder former, vacuum-assisted formation of the wet sheet, a dandy roll (which compresses the upper surface of the wet web), a vacuum-assisted pickup of the sheet from the cylinder, and a press nip (which often will have a felt run on each side of the compressed paper). A point worth noting is that various ingredients (some of which were listed in Fig. 6.1) can be added to the “thick stock” (often 2%–5% solids) shown entering the system from the lower right in the figure.
Melamine resin was shown to impart suitable wet strength for currency paper [Carson and Shaw 1946]. The mechanism of action has been described by Espy [1994, 1995]. Alternative wet-strength agents, such as polyamidoamine-epichlorohydrin resins, also can be used [Fischer 1996]. Although the wet-strength treatment is essential for durability, especially when banknotes go through the laundry, it becomes a problem when government authorities need to repulp the material. Espy and Geist [1993] showed that treatment with potassium permanganate, a strong oxidizing agent, is able to break down the cured melamine resin, facilitating repulping and allowing the fibers to be remade into paper. Fischer [1997] described a two-step process in which the wet-strength paper was first oxidized with peroxide at low pH, then hydrolyzed at high pH. More recently, Chen et al. [2012] found that a suitably high yield when repulping Chinese paper currency could be achieved by sequential treatment for 30 mins each in 5% sulfuric acid and 5% sodium hydroxide, followed by gentle mechanical refining.

Another key treatment is hydrophobic sizing, which is a second defense against the effects of wetting. It is well known that rosin sizing products work well under the acidic conditions associated with melamine usage [Gess 1991]. Surface sizing of banknote paper with glue and formaldehyde was found to enhance the print quality [Shaw and Bicking 1929].

Depending on the end-use requirements, it is likely that many grades of security paper, because of much lesser expectations of wear, will not require the exceptional strength of currency paper, and also the security features can be deployed differently. As a consequence, it may be more favorable to employ compositions more typical of modern printing papers (i.e., bleached kraft fibers, substantial quantities of calcium carbonate mineral to reduce costs while increasing opacity and achieving smoother paper, and starch at the size press to increase paper strength) [Neimo 1999].

### 6.5.4. Methods of Incorporating Features

When fine fibrous materials having a length between approximately 0.5 mm and 10 mm are mixed with papermaking furnish, one generally can expect that such materials will be retained efficiently within the paper as it is being formed. However, some of the security features that are either used or considered for use can be smaller than that, allowing the possibility that they might pass through the openings in the forming fabric. Papermakers routinely employ retention aids, often copolymers of acrylamide and a cationic derivative of acrylamide, to retain fine particles efficiently [Hubbe et al. 2009].

### 6.5.5. Erasure Resistance

Checks and other documents that may have printed monetary values, as well as signatures, can benefit from various tamper-evident features. To protect against mechanical erasure, several strategies can be used. For instance, paper can be prepared with a glossy coating that becomes dulled in an obvious way in response to erasure [Barthez and Bubois 1993]. Security papers also need to be resistant to various chemical agents that might be used to remove either printed text or a signature. A general approach is to treat the paper in some manner with chemicals that become discolored in the presence of various bleaches or solvents [Potolinca et al. 2017]. Honnorat and Riou [1991] coated paper with a combination of such compounds as zinc sulfate, gallic acid, 2,3,4-trihydroxyacetophenone, or 1,2,4-benzenetriolm, plus a binder. The same inventors...
[Honnorat and Riou 1992] claimed that such a coating exhibited obvious color changes upon treatment with bases, reducing agents, and eraser felts. Gessner [1969] and Muller and Nickel [1984] patented systems that develop coloration upon treatment with various oxidizing agents, such as bleaches. Camus [1986] patented a system that develops a strong color response to treatment with a reducing agent. Dussaud [1997] patented a system by which anything written on the front side of a document is carried through to the back, sometimes in a different color.

6.6. PAPER-BASED SECURITY FEATURES

Features that render banknotes and related documents resistant to copying can be added either during the paper forming process or during a subsequent printing process; features that can be added during formation of the paper will be considered in this section.

6.6.1. General

Some general features that often make banknotes recognizable to users include the fidelity of the background coloration, the sensed stiffness of the paper, and the quality of the graphics. Handlers often become suspicious of banknotes due to the look and feel [Bureau of Engraving and Printing 2006]. This can include a deviation in color, a waxy feel, or an unexpected degree of stiffness.

6.6.2. Inclusions Added During Papermaking

6.6.2.1. Threads

The manner in which paper is formed from a suspension of fibers lends itself to the inclusion of various threads, specialized fibers, and various specialized particles, which become incorporated randomly into the sheet [Bureau of Engraving and Printing 2006]. For example, as illustrated in Fig. 6.5., short pieces of colored thread can be added, usually as a minor component; such threads contribute to the overall background look of a banknote, and they also can be used to verify the denomination and legitimacy of a banknote [National Research Council 1993, 2007]. In principle, such fibers also could contain barcodes [Athey and Zorab 1998], thus providing an additional way to verify forgery after its detection.

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6.6.2.2. Fluorescent Items

Fluorescent effects provide means of distinguishing suitably prepared security papers, not only by machine readers, but also when a human observer uses UV illumination [National Research Council 2007]. For example, Basta et al. [2002, 2011] synthesized fluorescent compounds for addition to paper. Stenzel and Lehle [1979] claimed the use of certain rare-earth metal compounds having unique fluorescent spectral characteristics; such spectral responses can be evaluated with suitable spectrofluorometers. Related effects have been achieved using certain nanoparticulate materials [Chen et al. 2013; Basta et al. 2014; El-Sakhawy et al. 2015]. The narrow emission maxima of nanocrystals...
can easily be distinguished from the wide emission of ordinary fluorescent dyes and whitening agents [Chen et al. 2013]. Some specialized effects can be achieved by fluorescent treatment of fibers, which are later incorporated into paper [Boehm 1990; Lockie 1997]. For example, Boise Cascade company has sold security paper containing fluorescent fibers that become visible under UV light [Leupold 1991].

6.6.2.3. Other Inclusions

In addition to fibers, a wide variety of other small objects can be added, which can make the paper appear unique under reflected light, transmitted light, or specialized light sources. Such objects include planchets (bits of paper added at the wet end of a paper machine), taggants (color-coded objects that are machine detectable), iridescent features (which change color when viewed at different angles), objects showing dichroism (responding differently to polarized light in different planes), and phosphorescent objects (which re-emit light at a longer wavelength but not just immediately) [National Research Council 1993]. For example, Yang et al. [2017] described the use of photoluminescent “ultralong” hydroxyapatite nanowires that can be embedded in paper.

6.6.3. Modifications of the Paper

6.6.3.1. Watermarks

Localized changes in the thickness or density of paper can be imparted by suitable modifications in the forming fabric or wire-covered roll (dandy roll) that gets pressed against the wet web of paper during its dewatering (see Fig. 6.4). The modifications can include raised wires or three-dimensional shaping of one of the mesh surfaces that press against the newly formed wet paper [Lechiffre 1997]. The so-called “watermarks” resulting from such means have been widely used by papermakers since the middle ages in their attempts to make the paper uniquely distinguishable, especially when lighted from the back. For example, Fig. 6.6 shows a watermark that was prepared by using a metal screen as a forming fabric; the shape of the screen was modified to achieve subtle differences in the thickness and density of the paper in different areas. In principle, an area of greater density within paper has fewer voids and will scatter less light. Consequently, when held up to the light, the dark areas of watermarks become light areas, and vice versa [Lockie 1997]. Watermarks, when used in U.S. currency, are lined up to coincide with certain areas of the banknotes [National Research Council 1993; Lockie 1997], such as between the Federal Reserve seal and the border.

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6.6.3.2. Perforations

Microperforations have been considered as a feature that could be detected both by the general public and by machine [National Research Council 2007]. Beams of light passing directly through “pinholes” would be readily detectable.

6.6.3.3. Embossing

Whereas the term “watermark” implies imparting changes to the local thickness or density of paper while it is wet, changes also can be imparted after the paper is dry. The term “embossing” is used by papermakers to describe what happens when dry paper passes through a nip in which one of the surfaces has a hard pattern and the other surface is soft enough to be deformed, often permanently [Pasquale 1984]. In principle, suitable devices could be used to apply an embossing effect locally, for instance imparting a rough feel to a selected region of a security document [National Research Council 2007].

6.7. SECURITY FEATURES INVOLVING PRINTING

This section will consider various security features that can be applied onto the paper surface by various printing technologies.

6.7.1. Printing Methods

For a variety of reasons the results of certain high-volume printing technologies, which are designed for long, precise print runs, can produce results that are markedly different from those of xerographic printing, especially when viewed under the microscope or when they are felt with a sensitive finger. For instance, as illustrated in Fig. 6.7, intaglio or gravure printing, in which the ink is transferred to paper from engraved cavities within the surface of a printing applicator cylinder, tends to create raised letters having a distinguishable feel [Farroni 1986; National Research Council 1993, 2007]. By contrast, a letterpress operation tends to squeeze the ink during impression, often producing a ridge of ink at the outside edges of letters, lines, and dots [National Research Council 1993]. Xerographic or inkjet systems may have difficulty achieving the fine lines that can be produced by the legitimate printing operations for a certain type of currency.

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Although most printing of currency is highly repetitive, the serial number needs to advance for each successive banknote. Accordingly, especially when looking toward the future, there may be a role for nonimpact digital printing, especially inkjet printing. In addition to inkjet technology’s suitability for the printing of variable information such as serial numbers, it can be adapted to apply a wide range of materials, in addition to ordinary ink [Lin and He 2006]. The cited authors mentioned photochromic and thermochromatic inks that could be applied by inkjet.

6.7.2. Graphics Quality

By use of printing technologies, a manufacturer of security paper products can achieve a variety of results that are difficult to replicate with a color copier. Some of the more important will be summarized here. As noted earlier, the overall quality of printing of a banknote can be regarded as a first-line of challenge to any would-be forgers [Bureau of Engraving and Printing 2006]. Authorities can raise the challenge to higher levels by use of fine lines and small lettering, including so-called “microprinting” [National Research Council 1993] or “nanoprint” [National Research Council 2007]. By using suitable patterns of crossing lines, one can achieve moire images, which cause viewers and copying machines to “see” alias patterns that may not be explicitly present in the

Another way to create alias images that tend to be produced by a copier, while not being noticed by a human observer, is to vary the size of half-tone dots in a systematic way [National Research Council 1993].

6.7.3. Color of Printing

6.7.3.1. Multicolor Print

By selection of colors, and in particular by use of more than one color, the producer can achieve two key goals: recognizability and difficulty of accurate reproduction. Nonprimary hues, such as green or orange shades, possibly present greater challenge in terms of accurate reproduction on cheap devices because they generally require the combined usage of at least two colorants (e.g., a blue and a yellow). Also, the incorporation of larger numbers of print colors provides a larger barrier against precise copying [Bureau of Engraving and Printing 2006].

6.7.3.2. Color-Shifting Inks

Print produced with a color-shifting ink appears different depending on the angle of viewing, an effect that is also called iridescence. Such effects have been incorporated into U.S. currency and have become familiar to cash handlers [Bureau of Engraving and Printing 2006; National Research Council 2007]. Such effects also can be detected by mechanical devices [National Research Council 2007]. The mechanism involves the submicroscopic-scale structure of spacing within the material; this is in contrast with most colorants, which use chromophores to absorb light [Kinoshita and Yoshioka 2005]. Microstructures within the iridescent material give rise to effects that can be compared with that of a diffraction grating.

6.7.4. Fluorescence

A fluorescent colorant absorbs light at a shorter wavelength, some of the energy becomes lost, and the emitted light has a higher wavelength. The mechanism is illustrated in Fig. 6.8, which considers how the incident light can move one of the outermost electrons in the fluorescent compound to a higher energy level. The existence of multiple vibration states has the effect of spreading out the effects of ordinary fluorescent dyes over a wide range of wavelengths of the emitted light. Many papermakers are familiar with such effects because of the widespread usage of FWAs, which absorb invisible UV light and re-emit in the blue region [Crouse and Snow 1981].

By use of fluorescent inks of various kinds, a very wide range of spectral responses can be achieved. For this reason, effects related to fluorescent inks can be effective for detecting nonstandard banknotes [National Research Council 1993, 2007]. Figure 6.9 provides a schematic illustration of how fluorescent colorants such as a whitening agent and a fluorescent red dye would be expected to change the reflectance spectrum of paper. Fluorescent effects can be detected with very high sensitivity by using equipment that delivers a monochromatic incident light and detects the emission intensities at other wavelengths.

In addition to checking the central wavelengths of both incident light and the emitted light, it is also possible to detect differences in the lifetime of fluorescent effects after the illumination [Chia and Levene 2009]. Thus, the fluorescent lifetime results can be used as the basis of judging authenticity of a security document. Zhang et al. [2008] described metal enhancement of fluorescence effects and their use in resistance to counterfeiting.

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### 6.7.5. Infrared Ink

Infrared inks are designed to absorb light having longer wavelengths than can be detected by human vision. However, when added to a security document, they can be detected by suitable instruments and machine readers of currency [National Research Council 1993, 2007; Bureau of Engraving and Printing 2006].

### 6.7.6. Metamerism

The term “metamerism” describes the situation in which two objects may appear to have exactly the same color when viewed under one set of lighting conditions, but they appear to have different colors under a different condition of lighting. The effect can be achieved by employing combinations of dyes having distinctly different hues. For example, a brown color achieved with canary yellow, blue, and red dyes will tend to make a metameric match when the same brown is formed using an orange-yellow in combination with the same blue and red. This type of effect can be employed at low cost to achieve effects that can remain hidden under some lighting conditions but become obvious under others. Metamerism has been considered among other strategies for banknotes [National Research Council 1993, 2007].

### 6.7.7. Chromic Effects

Yet more optical effects can be achieved by inks that either change color upon continued light exposure (photochromic) or upon heating (thermochromic), or for which the emission of light occurs significantly later than the absorption (photoluminescent) [National Research Council 1993, 2007]. Lin and He [2006] noted that although photochromic and thermochromic effects have not often been used in security paper products, that situation can easily change now because of the maturation of inkjet printing technologies. Long et al. [2011] carried out tests to demonstrate the effectiveness and durability of a photochromic dye for use in security papers. Photoluminescent effects for security papers have been claimed in a series of patents by Kaule et al. [1984a–d, 1986].

### 6.7.8. Magnetic Inks

According to various sources, magnetic features are readily detectable by mechanical devices, as well as being able to be applied by means of magnetic inks [Devrient 1985; Mansour 1995; Bureau of Engraving and Printing 2006; National Research Council 2007]. For instance, devices can be set up that can read magnetic images [Devrient 1985]. By printing suitable lines or patterns, magnetism in the security paper can be detected by machine devices in which the paper may pass either lengthwise or sideways.
6.7.9. Printing Between Paper Plies

Although most paper, including currency paper, is presently manufactured as a single ply, some paper machine systems are set up to combine two separately formed damp plies, which are pressed together before the resulting sheet is dried [Hagglom-Ahnger 1999; Nordstrom 2016]. Such a forming system, if it were to be used for security paper products, could achieve effects that would be very difficult for a forger to replicate. If lamination were done in a dry condition, then printing could be applied to one or more of the interior surfaces [Detrick et al. 1992]. Alternatively, Holbein et al. [1985] claimed a system in which a color pattern is sprayed onto the interior surface of a still-damp ply of paper, which later is combined, pressed together, and dried together with a second ply of paper, leaving the image in the interior of the combined sheet. Such printing cannot be erased by mechanical means.

6.8. STRIPS AND SPECIALIZED INCLUSIONS

This section concerns specialized inclusions such as long strips, wires, windows, and holograms that would not be regarded as ordinary features of papermaking or printing. In other words, such features usually would require specialized equipment for their insertion into or onto paper.

6.8.1. Plastic Strip

U.S. banknotes having value of $5 or greater that have been produced in recent years contain a plastic security strip [Fuller 1984; Crane 1988, 1990; National Research Council 2007]. Such strips can be metalized or fluorescent and can contain identifying information [Crane 1991]. In U.S. currency the strips are 1.8 mm wide by 10–15 μm thick [National Research Council 1993]. Such strips can contain printed information that can be viewed in transmitted light from either side of the paper [Crane 1991; Burchard 1997]. A tiny graphic, such as an image of a flag, may be apparent [Bureau of Engraving and Printing 2006]. Another option is to employ partial metallization (i.e., metal markings [Melling and Knight 1990]). Figure 6.10 illustrates how a plastic strip, which is preprinted, can be included in paper during its formation, resulting in a nonerasable message that can be detected by holding the paper up to the light.

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6.8.2. Other Inclusions

Other kinds of inclusions, which may require special equipment to insert into or onto security documents, may include wires [Lockie 1997], windows [Melling and Knight 1993], holograms [Barnoin et al. 1995], and smart chips of various kinds. Holograms can be effective against copying, but concerns have been raised about their durability [National Research Council 1993]. On the other hand, such features can be used with checks or tickets, noting the lesser concerns about accumulated wear in those cases.

6.9. CONCLUSIONS
In some respects the manufacture of security paper products can be regarded as a well-established field having known technologies and production strategies. On the other hand, there is a very wide diversity of methods and systems to protect against forgery, either by making the product recognizable or by being able to verify genuineness with confidence. Because the banknotes, tickets, and certificates, among others, can represent high value relative to the materials of preparation, there are clearly opportunities for a company to achieve favorable profit margins. The field also remains attractive for scientists and inventors to explore new ways to deal with forensic and product development issues.

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FIGURES

**PAPERMAKING**

<table>
<thead>
<tr>
<th>Additions to the fiber slurry</th>
<th>PRINTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber types</td>
<td>Multi-color</td>
</tr>
<tr>
<td>Dyes</td>
<td>Fluorescent ink</td>
</tr>
<tr>
<td>Threads</td>
<td>Infra-red ink</td>
</tr>
<tr>
<td>Bits of paper</td>
<td>Magnetic ink</td>
</tr>
<tr>
<td>Modifications to the wet paper</td>
<td>Metamerism</td>
</tr>
<tr>
<td>Wire mark</td>
<td>Color-shifting ink</td>
</tr>
<tr>
<td>Watermarks</td>
<td>Moire patterns</td>
</tr>
<tr>
<td>Insertions between paper plies</td>
<td>Fine lines</td>
</tr>
<tr>
<td>Plastic strips</td>
<td>Nanoprint</td>
</tr>
<tr>
<td>Printing in paper’s interior</td>
<td>Intaglio feel</td>
</tr>
</tbody>
</table>

**Figure 6.1.** Listing of some important security features that can be incorporated into or onto paper products during formation of the paper and during subsequent printing.

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**Figure 6.2.** Representations of typical lengths of fibers from cotton and flax (see mm scale at top), and sketches of fiber structure. (Drawing of the cotton cell wall structure is based on a detailed drawing by Wakelyn et al. [2006].)
Figure 6.3. Schematic illustration of how a pH-sensitive marker can be employed to reveal paper documents that have been prepared from an inappropriate type of paper (e.g., copy paper).

Figure 6.4. Sketch of one type of paper machine system that could be employed for forming security paper, which may include relatively long fibers, colored threads, and other materials.
Figure 6.5. Sketch representing how inclusions such as chopped fiber thread can be added to the fiber furnish of a paper machine system, giving rise to a distinctive appearance of the paper.

Figure 6.6. This example of a watermark is a photograph from a back-lit original at the Robert C. Williams American Museum of Papermaking. (Published with permission by Hubbe and Bowden [2009].)
Figure 6.7. Schematic illustration of contrasting print features resulting from two of the printing methods that are often considered for production of currency.

Figure 6.8. Illustration of mechanism by which fluorescent materials absorb light of a shorter wavelength (higher energy), lose some of the energy as heat due to the existence of closely spaced vibrational energy levels, and re-emit the energy at a longer wavelength.
Figure 6.9. Depiction of the kinds of changes to the reflectance spectrum of paper caused by the presence of two kinds of fluorescent dyes, one being a typical fluorescent whitening agent and the other being a fluorescent red dye.

Figure 6.10. Representation of the way that a printed plastic strip, embedded within the core of paper, can reveal a printed image (e.g., USA 100) when lighted from behind.