chapter 7

The Microscope

Key Terms

binocular

condenser

depth of focus

eyepiece lens

field of view

microspectrophotometer

monocular

objective lens

parfocal

plane-polarized light

polarizer

real image

transmitted illumination

vertical or reflected illumination

virtual image

Learning Objectives

After studying this chapter you should be able to:

- List and understand the parts of the compound microscope
- Define magnification, field of view, working distance, and depth of focus
- Contrast the comparison and compound microscopes
- Understand the theory and utility of the stereoscopic microscope
- Appreciate how a polarizing microscope is designed to characterize polarized light
- Appreciate how a microspectrophotometer can be used to examine trace physical evidence
- Compare and contrast the image formation mechanism of a light microscope to that of a scanning electron microscope
- Outline some forensic applications of the scanning electron microscope

The Lindbergh Baby Case

On the evening of March 1, 1932, a kidnapper crept up his homemade ladder and stole the baby of Charles and Anne Lindbergh directly from the second-floor nursery of their house in Hopewell, New Jersey. The only evidence of his coming was a ransom note, the ladder, a chisel, and the tragic absence of the infant. A couple of months later, though the $50,000 ransom had been paid, the baby turned up dead in the woods a mile away. There was no additional sign of the killer. Fortunately, when finally studied by wood technologist Arthur Koehler, the abandoned ladder yielded some important investigative clues (see case study on page 198).

By studying the types of wood used and the cutter marks on the wood, Koehler ascertained where the materials might have come from and what specific equipment was used to create them. Koehler traced the wood from a South Carolina mill to a lumberyard in the Bronx, New York. Unfortunately the trail went cold, as the lumberyard did not keep sales records of purchases. The break in the case came in 1934, when Bruno Richard Hauptmann paid for gasoline with a bill that matched a serial number on the ransom money. Koehler showed that microscopic markings on the wood were made by a tool in Hauptmann's possession. Ultimately, handwriting analysis of the ransom note clearly showed it to be written by Hauptmann.

A microscope is an optical instrument that uses a lens or a combination of lenses to magnify and resolve the fine details of an object. The earliest methods for examining physical evidence in crime laboratories relied almost solely on the microscope to study the structure and composition of matter. Even the advent of modern analytical instrumentation and techniques has done little to diminish the usefulness of the microscope for forensic analysis. If anything, the development of the powerful scanning electron microscope promises to add a new dimension to forensic science heretofore unattainable within the limits of the ordinary light microscope.

The earliest and simplest microscope was the single lens commonly referred to as a *magnifying glass*. The handheld magnifying glass makes things appear larger than they are because of the way light rays are refracted, or bent, in passing from the air into the glass and back into the air. The magnified image is observed by looking through the lens, as shown in Figure 7–1. Such an image is known as a **virtual image**; it can be seen only by looking through a lens and cannot be viewed directly. This is distinguished from a **real image**, which can be seen directly, like the image that is projected onto a motion picture screen.

The ordinary magnifying glass can achieve a magnification of about 5 to 10 times. Higher magnifying power is obtainable only with a *compound microscope*, constructed of two lenses mounted at each end of a hollow tube. The object to be magnified is placed under the lower lens, called the **objective lens**, and the magnified image is viewed through the upper lens, known as the **eyepiece lens**. As shown in Figure 7–2, the objective lens forms a real, inverted, magnified image of the object. The eyepiece, acting just like a simple magnifying glass, further magnifies this image into a virtual image, which is what is seen by the eye. The combined magnifying power of both lenses can produce an image magnified up to 1,500 times.

The optical principles of the compound microscope are incorporated into the basic design of different types of light microscopes. The microscopes most applicable for examining forensic specimens are as follows:

1. The compound microscope
2. The comparison microscope
3. The stereoscopic microscope
4. The polarizing microscope
5. The microspectrophotometer

After describing these five microscopes, we will talk about a completely different approach to microscopy, the scanning electron microscope (SEM). This instrument focuses a beam of electrons, instead of visible light, onto the specimen to produce a magnified image. The principle and design of this microscope permit magnifying powers as high as 100,000 times.

THE COMPOUND MICROSCOPE

The parts of the compound microscope are illustrated in Figure 7–3(a). Basically, this microscope consists of a mechanical system, which supports the microscope, and an optical system. The optical system illuminates the object under investigation and passes the light through a series of lenses to form an image of the specimen on the retina of the eye. The optical path of light through a compound microscope is shown in Figure 7–3(b).

The mechanical system is composed of six parts:

Base (1). The support on which the instrument rests.

Arm (2). A C-shaped upright structure, hinged to the base, that supports the microscope and acts as a handle for carrying.

Stage (3). The horizontal plate on which the specimens are placed for study. The specimens are normally mounted on glass slides that are held firmly in place on the stage by spring clips.

Body tube (4). A cylindrical hollow tube on which the objective and eyepiece lenses are mounted at opposite ends. This tube merely serves as a corridor through which light passes from one lens to another.

Coarse adjustment (5). This knob focuses the microscope lenses on the specimen by raising and lowering the body tube.

Fine adjustment (6). The movements effected by this knob are similar to those of the coarse adjustment but are of a much smaller magnitude.

The optical system is made up of four parts:

Illuminator (7). Most modern microscopes use artificial light supplied by a lightbulb to il-

luminate the specimen being examined. If the specimen is transparent, the light is directed up toward and through the specimen stage from an illuminator built into the base of the microscope. This is known as **transmitted illumination**. When the object is opaque—that is, not transparent—the light source must be placed above the specimen so that it can reflect off the specimen's surface and into the lens system of the microscope. This type of illumination is known as **vertical** or **reflected illumination**.

Condenser (8). The **condenser** collects light rays from the base illuminator and concentrates them on the specimen. The simplest condenser is known as the *Abbé condenser*. It consists of two lenses held together in a metal mount. The condenser also includes an iris diaphragm that can be opened or closed to control the amount of light passing into the condenser.

Objective lens (9). This is the lens positioned closest to the specimen. To facilitate changing from one objective lens to another, several objectives are mounted on a revolving nosepiece or turret located above the specimen. Most microscopes are **parfocal**, meaning that when the microscope is focused with one objective in position, the other objective can be rotated into place by revolving the nosepiece while the specimen remains very nearly in correct focus.

Eyepiece or ocular lens (10). This is the lens closest to the eye. A microscope with only one eyepiece is **monocular**; one constructed with two eyepieces (one for each eye) is **binocular**.

Each microscope lens is inscribed with a number signifying its magnifying power. The image viewed by the microscopist will have a total magnification equal to the product of the magnifying power of the objective and eyepiece lenses. For example, an eyepiece lens with a magnification of 10 times (10×) used in combination with an objective lens of 10 times has a total magnification power of 100 times (100×). Most forensic work requires a 10× eyepiece in combination

with either a 4×, 10×, 20×, or 45× objective. The respective magnifications will be 40×, 100×, 200×, and 450×.

In addition, each objective lens is inscribed with its numerical aperture (N.A.). The ability of an objective lens to resolve details into separate images instead of one blurred image is directly proportional to the numerical aperture value of the objective lens. For example, an objective lens of N.A. 1.30 can separate details at half the distance of a lens with an N.A. of 0.65. The maximum useful magnification of a compound microscope is approximately 1,000 times the N.A. of the objective being used. This magnification is sufficient to permit the eye to see all the detail that can be resolved. Any effort to increase the total magnification beyond this figure will yield no additional detail and is referred to as *empty magnification*.

Although a new student of the microscope may be tempted to immediately choose the highest magnifying power available to view a specimen, the experienced microscopist weighs a number of important factors before choosing a magnifying power. A first consideration must be the size of the specimen area, or the **field of view**, that the examiner wishes to study. As magnifying power increases, the field of view decreases. Thus, it is best to first select a low magnification in which a good general overall view of the specimen is seen and to switch later to a higher power in which a smaller portion of the specimen can be viewed in more detail.

The **depth of focus** is also a function of magnifying power. After a focus has been achieved on a specimen, the depth of focus defines the thickness of that specimen. Areas above and below this region will be blurred and can be viewed only when the focus is readjusted. Depth of focus decreases as magnifying power increases.

THE COMPARISON MICROSCOPE

Forensic microscopy often requires a side-by-side comparison of specimens. This kind of examination can best be performed with a comparison microscope, such as the one pictured in Figure 7–4. Basically, the comparison microscope is two compound microscopes combined into one unit. The unique feature of its design is that it uses a bridge incorporating a series of mirrors and lenses to join two independent objective lenses into a single binocular unit. When a viewer looks through the eyepiece lenses of the comparison microscope, a circular field, equally divided into two parts by a fine line, is observed. The specimen mounted under the left-hand objective is seen in the left half of the field, and the specimen under the right-hand objective is observed in the right half of the field. It is important to closely match the optical characteristics of the objective lenses to ensure that both specimens are seen at equal magnification and with minimal but identical lens distortions. Comparison microscopes designed to compare bullets, cartridges, and other opaque objects are equipped with vertical or reflected illumination. Comparison microscopes used to compare hairs or fibers use transmitted illumination.

Figure 7–5 shows the striation markings on two bullets that have been placed under the objective lenses of a comparison microscope. Modern firearms examination began with the introduction of the comparison microscope, with its ability to give the firearms examiner a side-by-side magnified view of bullets. Bullets that are fired through the same rifle barrel display comparable rifling markings on their surfaces. Matching the majority of striations present on each bullet justifies a conclusion that both bullets traveled through the same barrel.

THE STEREOSCOPIC MICROSCOPE

The details that characterize the structures of many types of physical evidence do not always require examination under very high magnifications. For such specimens, the stereoscopic micro-

scope has proven quite adequate, providing magnifying powers from 10× to 125×. This microscope has the advantage of presenting a distinctive three-dimensional image of an object. Also, whereas the image formed by the compound microscope is inverted and reversed (upside-down and backward), the stereoscopic microscope is more convenient because of the prisms in its light path that permit the formation of a right-side-up image. The stereoscopic microscope, shown in Figure 7–6, is actually two monocular compound microscopes properly spaced and aligned to present a three-dimensional image of a specimen to the viewer, who looks through both eyepiece lenses. The light path of a stereoscopic microscope is shown in Figure 7–7.

The stereoscopic microscope is undoubtedly the most frequently used and versatile microscope found in the crime laboratory. Its wide field of view and great depth of focus make it an ideal instrument for locating trace evidence in debris, garments, weapons, or tools. Furthermore, its potentially large *working distance* (the distance between the objective lens and the specimen) makes it quite applicable for the microscopic examination of big, bulky items. When fitted with vertical illumination, the stereoscopic microscope becomes the primary tool for characterizing physical evidence as diverse as paint, soil, gunpowder residues, and marijuana.

THE POLARIZING MICROSCOPE

Recall from Chapter 5 that light's wavelike motion in space can be invoked to explain many facets of its behavior. The waves that compose a beam of light can be pictured as vibrating in all directions perpendicular to the direction in which the light is traveling. However, when a beam of light passes through certain types of specially fabricated crystalline substances, it emerges vibrating in only one plane. Light that is confined to a single plane of vibration is said to be **plane-polarized**. The device that polarizes light in this manner is called a **polarizer**. A common exam-

ple of this phenomenon is the passage of sunlight through polarized sunglasses. By transmitting light vibrating in the vertical plane only, these sunglasses eliminate or reduce light glare. Most glare consists of partially polarized light that has been reflected off horizontal surfaces and thus is vibrating in a horizontal plane.

Because polarized light appears no different to the eye from ordinary light, special means must be devised for detecting it. This is accomplished simply by placing a second polarizing crystal, called an *analyzer*, in the path of the polarized beam. As shown in Figure 7–8, if the polarizer and analyzer are aligned parallel to each other, the polarized light passes through and is seen by the eye. If, on the other hand, the polarizer and analyzer are set perpendicular to one another, or are "crossed," no light penetrates, and the result is total darkness or *extinction*.

In this manner, a compound or stereoscopic microscope can be outfitted with a polarizer and analyzer to allow the viewer to detect polarized light. Such a microscope is known as a *polarizing microscope*. Essentially, the polarizer is placed between the light source and the sample stage to polarize the light before it passes through the specimen. The polarized light penetrating the specimen must then pass through an analyzer before it reaches the eyepiece and finally the eye. Normally, the polarizer and analyzer are "crossed" so that when no specimen is in place, the field appears dark. However, introducing a specimen that polarizes light reorients the polarized light, allowing it to pass through the analyzer. This result produces vivid colors and intensity contrasts that make the specimen readily distinguishable.

The most obvious and important applications of this microscope relate to studying materials that polarize light. For example, as we learned in Chapter 4 (see pp. 108–109), many crystalline substances are birefringent; that is, they split a beam of light into two light-ray components of different refractive index values. What makes this observation particularly relevant to our dis-

cussion of the polarizing microscope is that the light beams are polarized at right angles to each other. Thus, polarizing microscopy has found wide application for the examination of birefringent minerals present in soil. By using the immersion method (see pp. 111–112) and selecting the proper immersion liquids, a refractive index corresponding to each plane of polarized light can be determined. Thus, when a mineral is viewed under polarized light in a liquid that matches one of its refractive indices, the Becke line will no longer be visible. This information, plus observations on crystal color, form, and so on, makes it possible for the microscopist to identify the mineral. Similarly, criminalists use the fact that many synthetic fibers are birefringent to characterize them with a polarizing microscope.

THE MICROSPECTROPHOTOMETER

From a practical point of view, few instruments in a crime laboratory can match the versatility of the microscope. The microscope's magnifying power is indispensable for finding minute traces of physical evidence. Many items of physical evidence can be characterized by a microscopic examination of their morphological features. Likewise, the microscope can be used to study how light interacts with the material under investigation, or it can be used to observe the effects that other chemical substances have on such evidence. Each of these features allows an examiner to better characterize and identify physical evidence. Recently, linking the microscope to a computerized spectrophotometer has added a new dimension to its capability. This combination has given rise to a new instrument called the **microspectrophotometer**.

In many respects, this is an ideal marriage from the forensic scientist's viewpoint. In Chapter 5, we saw how a chemist can use selective absorption of light by materials to characterize them. In particular, light in the ultraviolet, visible, and infrared regions of the electromagnetic spec-

trum is most helpful for this purpose. Unfortunately, in the past, forensic chemists were unable to take full advantage of the capabilities of spectrophotometry for examining trace evidence, because most spectrophotometers are not well suited for examining the very small particles frequently encountered as evidence. However, with the development of the microspectrophotometer, a forensic analyst can now view a particle under a microscope while a beam of light is directed at the particle in order to obtain its absorption spectrum. Depending on the type of light employed, an examiner can acquire either a visible or an IR spectral pattern of the substance being viewed under the microscope. The obvious advantage of this approach is to provide the forensic scientist with added information that will characterize trace quantities of evidence. A microspectrophotometer designed to measure the uptake of visible light by materials is shown in Figure 7–9.

Visual comparison of color is usually one of the first steps in examining paint, fiber, and ink evidence. Such comparisons are easily obtained using a comparison microscope. Now, with the use of the microspectrophotometer, not only can the color of materials be compared visually but, at the same time, an absorption spectrum can be plotted for each item under examination to display the exact wavelengths at which it absorbs in the visible-light spectrum. Occasionally colors that appear similar by visual examination show significant differences in their absorption spectra. An example of this approach is shown in Figure 7–10, in which the microspectrophotometer is used to distinguish counterfeit and authentic currency by comparing the spectral patterns of inked lines on currency.

Another emerging technique in forensic science is the use of the infrared microspectrophotometer to examine fibers and paints. The “fingerprint” IR spectrum (see p. 150) is unique for each chemical substance. Therefore, obtaining such a spectrum from either a fiber or a paint chip

allows the analyst to better identify and compare the type of chemicals from which these materials are manufactured. With a microspectrophotometer, a forensic analyst can view a substance through the microscope and at the same time have the instrument plot the infrared absorption spectrum for that material.

THE SCANNING ELECTRON MICROSCOPE (SEM)

All the microscopes described thus far use light coming off the specimen to produce a magnified image. The scanning electron microscope is, however, a special case in the family of microscopes (see Figure 7–11). The image is formed by aiming a beam of electrons onto the specimen and studying electron emissions on a closed TV circuit. The beam of electrons is emitted from a hot tungsten filament and is focused by electromagnets onto the surface of the specimen. This primary electron beam causes the emission of electrons, known as secondary electrons, from the elements that make up the upper layers of the specimen. Also, 20 to 30 percent of the primary electrons rebound off the surface. These electrons are known as *backscattered electrons*. The emitted electrons (both secondary and backscattered) are collected and the amplified signal is displayed on a cathode-ray or TV tube. By scanning the primary electron beam across the specimen's surface in synchronization with the cathode-ray tube, it is possible to convert the emitted electrons into an image of the specimen for display on the cathode-ray tube.

The major attractions of the SEM image are its high magnification, high resolution, and great depth of focus. In its usual mode, the SEM has a magnification that ranges from 10× to 100,000×. Its depth of focus is some 300 times better than optical systems at similar magnifications, and the resultant picture is almost stereoscopic in appearance. Its great depth of field and magnification are exemplified by the magnification of cystolithic hair on the marijuana leaf, as

shown in Figure 7–12. An SEM image of a vehicle's headlight filaments may reveal whether the headlights were on or off at the time of a collision (see Figures 7–13 and 7–14).

Another facet of scanning electron microscopy has been the use of X-ray production to determine the elemental composition of a specimen. X-rays are generated when the electron beam of the scanning electron microscope strikes a target. When the SEM is coupled to an X-ray analyzer, the emitted X-rays can be sorted according to their energy values and used to build up a picture of the elemental distribution in the specimen. Because each element emits X-rays of characteristic energy values, the X-ray analyzer can identify the elements present in a specimen. Furthermore, the element's concentration can be determined by measuring the intensity of the X-ray emission.

One application of scanning electron microscopy has been to determine whether a suspect has recently fired a gun. In this case, an attempt is made to remove any gunshot particles that remain on a shooter's hands by lifting them off with a piece of adhesive tape. The tape is then examined under the SEM for the presence of particles that may have originated from the bullet primer. These particles can be characterized by their size, shape, and elemental composition. As shown in Figure 7–15, when the sample of gunshot residue is exposed to a beam of electrons from the scanning electron microscope, X-rays are emitted. These X-rays are passed into a detector, where they are converted into electrical signals. These signals are sorted and displayed according to the energies of the emitted X-rays. Through the use of this technique, the elements lead, antimony, and barium, frequently found in most primers, can be rapidly detected and identified.

Chapter Summary

A microscope is an optical instrument that uses a lens or a combination of lenses to magnify and resolve the fine details of an object. Various types of microscopes are used to analyze forensic specimens. In the basic compound microscope, the object to be magnified is placed under the lower lens, called the objective lens, and the magnified image is viewed through the upper lens, known as the eyepiece lens. Forensic microscopy often requires side-by-side comparison of specimens. The comparison microscope consists of two independent objective lenses joined together by an optical bridge to a common eyepiece lens. When a viewer looks through the eyepiece lens of the comparison microscope, the objects under investigation are observed side-by-side in a circular field that is equally divided into two parts. Modern firearms examination began with the introduction of the comparison microscope, with its ability to give the firearms examiner a side-by-side magnified view of bullets. The stereoscopic microscope is actually two monocular compound microscopes properly spaced and aligned to present a three-dimensional image of a specimen to the viewer, who looks through both eyepiece lenses. Its large working distance makes it quite applicable for the microscopic examination of big, bulky items.

Light that is confined to a single plane of vibration is said to be plane-polarized. The examination of the interaction of plane-polarized light with matter is made possible with the polarizing microscope. Polarizing microscopy has found wide applications for the study of birefringent materials, that is, materials that have a double refraction. These refractive index data help identify minerals present in a soil sample or the identity of a manufactured fiber. The microspectrophotometer is a spectrophotometer coupled with a light microscope. The examiner studying a specimen under a microscope can simultaneously obtain the visible absorption spectrum or IR spectrum of the material being observed.

Finally, the scanning electron microscope (SEM) bombards a specimen with a beam of elec-

trons instead of light to produce a highly magnified image from 10× to 100,000×. The bombardment of the specimen's surface with electrons normally produces X-ray emissions that can be used to characterize elements present in the material under investigation.

Review Questions

1. A microscope uses a combination of _____ to magnify an image.
2. A type of image that cannot be viewed directly is called a(n) _____ image.
3. A(n) _____ microscope consists of two lenses mounted at each end of a hollow tube.
4. The lens closest to the specimen is called the _____.
5. The lens nearest the viewer's eye is called the _____.
6. The image seen through a compound microscope is (virtual, real).
7. True or False: The coarse and fine adjustments are part of the microscope's mechanical system. _____
8. A transparent specimen is viewed through a microscope using _____ light.
9. An opaque object requires _____ illumination for viewing with a microscope.
10. A(n) _____ collects light rays from the base illuminator and concentrates them on the specimen.
11. A microscope that remains in focus regardless of which objective lens is rotated into place is _____.
12. A microscope with only one eyepiece is _____; one with two eyepieces is _____.

13. Each microscope lens is inscribed with a number signifying its _____.

14. An eyepiece lens of 10× used in combination with an objective lens of 20× has a total magnification power of _____.

15. The ability of an objective lens to resolve details into separate images is directly proportional to its _____.

16. The size of the specimen area in view is known as the _____.

17. As magnification increases, the field of view (increases, decreases).

18. The thickness of a specimen in view is known as the _____.

19. The depth of focus (increases, decreases) with increasing magnification.

20. A side-by-side view of two specimens is best obtained with the _____ microscope.

21. True or False: A bridge is used to join two independent objective lenses into a single binocular unit to form a comparison microscope. _____

22. Two monocular compound microscopes properly spaced and aligned describe the _____ microscope.

23. True or False: The stereoscopic microscope is the least frequently used microscope in a typical crime laboratory. _____

24. The stereoscopic microscope offers a large _____ between the objective lens and the specimen.

25. Light confined to a single plane of vibration is said to be _____.

26. If a polarizer and analyzer are placed (perpendicular, parallel) to each other, no light pene-

trates.

27. The _____ microscope allows a viewer to detect polarized light.

28. Crystals that are _____ produce two planes of polarized light, each perpendicular to the other.

29. By using the _____, one can view a particle under a microscope while a beam of light is directed at the particle in order to obtain its absorption spectrum.

30. The _____ microscope focuses a beam of electrons on a specimen to produce an image.

31. When a beam of electrons strikes a specimen, _____ are emitted whose energies correspond to elements present in the specimen.

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Case Study

Microscopic Trace Evidence—The Overlooked Clue

Arthur Koehler—Wood Detective

Skip Palenik

Walter C. McCrone Associates Inc.

… Arthur Koehler … wood technologist and chief of the division of silvicultural relations at the U.S. Forest Products Laboratory in Madison, Wisconsin, … was born on June 4, 1885, in Mishicot, Wisconsin. His father was a carpenter and young Koehler grew up on a farm with a love of both wood and fine tools. This love naturally led him into forestry and he received a B.S. degree in the subject from the University of Michigan in 1911…. Upon graduation he went to work for the U.S. Forest Service in Washington, D.C., and three years later obtained a post at the U.S. Forest Products Laboratory where he served in various capacities until his retirement.

Although his primary responsibilities lay in wood identification and the correlation of micro-

scopic wood structure and end use, Koehler also began to build a reputation as a wood detective after his success in obtaining evidence from wood fragments which were submitted to the laboratory in several cases of local importance…. The case which thrust Koehler into the limelight of international publicity, however, was the Lindbergh kidnapping case in which he, by the most painstaking work, traced the kidnap ladder back to the lumberyard from which its constituent parts had been purchased.

Sometime between the hours of 8 and 10 p.m. on the night of March 1, 1932, a kidnapper climbed into the nursery of the newly completed home of Charles and Anne Lindbergh in Hopewell, New Jersey, and abducted their infant son. The only clues left behind were a few indistinct muddy footprints, a ransom note in the nursery, a homemade ladder and a chisel found a short distance from the house. Scarcely two months later, on May 12, the dead body of the child was found, half buried in the woods, about a mile from the Lindbergh home. One of the most intensive manhunts in U.S. history ensued, but failed to uncover any trace of the kidnapper or the ransom money which had been paid.[1]

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Shortly after the news of the kidnapping broke in the press Koehler wrote a letter to Colonel Lindbergh offering his services to help with the investigation of the ladder. He never received a reply (which was not surprising considering the flood of mail which arrived at the Lindbergh home in the weeks following the kidnapping). He was not entirely surprised though when his boss, Carlyle P. Winslow, placed before him some slivers of the ladder with the request that the wood be accurately identified.[2] This Koehler did, noting in his report the presence of golden

brown, white and black wool fibers which he speculated might be from clothing worn by the kidnapper. That was the last he heard about the ladder for almost a year. During this time it was carried around the country (carefully wrapped in a wool blanket) to various experts including specialists at the National Bureau of Standards.[3] However, after a year of investigation the authorities were no closer to arresting a suspect than they were the day after the crime.

It was almost a year after the kidnapping when Koehler was asked by the head of the U.S. Forest Service, Major Robert Y. Stuart, to travel to Trenton to give the ladder an in-depth examination. Discussions between Colonel Norman Schwarzkopf, who headed the New Jersey State Police (and the kidnap investigation), and Major Stuart had convinced Colonel Schwarzkopf that the ladder might still yield clues about its maker if Koehler were given a chance to examine it thoroughly. Schwarzkopf wasn't too certain about Koehler's ability ("Wasn't he the one who identified the blanket fibers on the wood we sent him?" he asked) but felt he had nothing to lose.

For the first time, Koehler saw the ladder (Figure 1). He was immediately struck by the fact that, although it was cleverly contrived, it was shamefully constructed. Instead of rungs it had cleats, which had been carelessly mortised with a dull chisel. A dull hand plane had been used needlessly in some places and a handsaw had been drawn carelessly across some of the boards.

Alone for four days, Koehler studied the ladder in the police training school in Wilburtha. He then returned to the Forest Products Laboratory with the ladder and closed himself up in a private laboratory with the best optical equipment available.[4] He began by completely dissecting the ladder into its component parts. Each piece was numbered. The cleats were labeled 1 (bottom) through 11 (top). The rails were numbered starting from 12 (bottom left) to 17 (right-hand top)…. Each mark was noted and indexed. After probing with microscopes, calipers and a vari-

ety of lighting and photographic techniques, the ladder slowly began to give up its secrets.

The sheer number of observations, facts and deductions about the origin of the ladder (and its producer) made by Koehler are truly staggering. We are concerned here only with those facts and observations which (1) allowed the parts to be traced and (2) described the carpenter and the previous environment of the ladder. The results were presented not as the subject of a single report but of daily letters to the director of the laboratory. As certain aspects were revealed they were pursued until the object could be traced no further. The most pertinent observations and deductions are listed and described below.

1. Microscopical examination showed four types of wood were used (Table 1). North Carolina pine is a trade name for wood from the southern yellow pine group which grows in commercial stands in the Southern U.S. along the Gulf of Mexico and along the Eastern Seaboard up into New Jersey and southern New York.[5] Douglas fir and ponderosa pine grow in the Western U.S. and birch is found throughout the country.[6]

2. Rails 12 and 13 showed faint marks which gave information about the planer in the mill where the wood was dressed…. Figure 2 shows the operation of a mill planer in diagrammatic form. Defects in the cutters allowed the number of knives in the cutters to be determined by counting cutter marks between defect marks. Eight cutter heads dressed the wide surface and six heads the edges….

Table 1 Woods Used in Kidnap Ladder

Cleats	
1–10	**Ponderosa pine**

		1 × 6-inch boards ripped lengthwise into strips 2¾ inches wide to make cleats.
	11	**Douglas fir** Grain matched bottom of rail 15.
Side Rails		
	12, 13—	**North Carolina pine.** Second growth. Cut from one board originally 14 feet long. Dressed to 3¾ inches in width. Both dressed on same planer.
	14, 15—	**Douglas fir** Dressed on two different planers.
	16—	**North Carolina pine** Narrowed from a wider board as indicated by handsaw and hand-planer marks on edges.
	17—	**Douglas fir** Dressed on different planers than 14 and 15.
Dowel Pins		
		Birch

The lumber went through the planer at a rate of 0.93 inches per complete revolution of the top and bottom cutter heads and 0.86 inches per revolution of the cutter heads that dressed the edges.

This was determined by the distance of identical cuts made by a defective knife on each surface….[7] Using the fact that the cutters in mill planers are usually driven at 3600 revolutions per minute it was possible to calculate the speed at which the wood passed into the planer as 258 feet per minute for the edge and 279 feet per minute for the board surfaces. The difference in the speed of the horizontal and vertical heads indicated that the planer was belt driven.

3. Rail 16 had four nail holes made by old fashioned square cut 8-penny nails. The holes had no connection with the construction of the ladder and therefore indicated prior use. The nail holes were clean and free from rust indicating inside use. This was confirmed by the general appearance of the rail which, although sapwood, showed no sign of exposure to the weather for any length of time since it was bright and unchecked. Therefore, it must have been nailed down indoors. Since it was low-grade lumber it would not have been used for finish purposes, but for rough construction. The spacing of the nails at 16 and 32 inches was considered significant and the suggestion was made that the rail came from the interior of a barn, garage or attic.

After an initial, futile attempt to trace the birch dowels, Koehler set out to try and trace the North Carolina rails (numbers 12 and 13). Although North Carolina pine grew in a large region it would not be profitable to ship it far, and since the ladder had turned up in New Jersey he felt certain that it had been milled somewhere in the Atlantic States. Using the Southern Lumberman's Directory, a list of 1598 planing mills from Alabama to New York was compiled. A confidential letter from Colonel Schwarzkopf and a two-page description written by Koehler were sent off to all of the mills on the list.

Of all the letters sent, only 25 mills reported having planers which matched the specifications

outlined in the letter. Two were immediately excluded since they didn't dress lumber of the requisite size. Samples of 1- × 4-inch wood were requested from each of the remaining 23 mills. A sample received from the M. G. and J. J. Dorn mill of McCormick, South Carolina, showed exactly the marks Koehler was looking for.

A visit to the mill showed that the particular spacing was due to a pulley which had been purchased in September of 1929. The records of the mill showed that forty-six carloads of 1×4 had been shipped north of the Potomac River in the time between the purchases of the pulley and the kidnapping…. After personally visiting the final destination of each of the shipments, Koehler and Detective Bornmann finally arrived at a Bronx firm, the National Lumber and Millwork Company. Although the entire shipment had long before been sold, the foreman remembered that some storage bins had been built from some of the wood. The wood matched that from the ladder perfectly (Figures 3 and 4). Examination of wood from shipments before and after the Bronx carload showed that the belt on the planer had been changed and the knife sharpened. This meant that this shipment was the only one from which the two particular rails from the attic could have come. Whoever built the ladder had purchased part of the wood here!

Koehler was unprepared for the foreman's answer to his request to see the sales records. They had none. They had started selling cash and carry sometime before the Dorn shipment arrived and had no records. Although he had failed to come up with the carpenter's name, the authorities at least now knew the region where the kidnapper lived and bought his wood for the ladder.

Koehler went back to his laboratory and, undaunted, started tracing the Douglas fir rails. At the time a suspect was arrested, he had succeeded in tracing one of the boards to a mill in Bend, Oregon, and another to Spokane, Washington. With the arrest of Richard Hauptmann on Sep-

tember 19, 1934, … his role in the case changed from an investigative to a comparative one. In Hauptmann's garage a variety of tools were found whose markings could be compared with those from the ladder. Comparative micrographs of marks made with Hauptmann's plane and plane marks on the ladder showed that his plane was used to plane the cleats (Figure 5). Finally, one of the investigators searching the attic of the suspect's home found that a board had been sawed out of the floor (Figure 6). Koehler's examination showed that the nail holes in the floor joists and the ladder rail (No. 16) aligned perfectly. A detailed analysis of the grain and wood itself showed that rail 16 and the section of board remaining in the attic were originally all one piece (Figure 7 and Figure 8).

Richard Bruno Hauptmann was convicted and sentenced to death in a sensational trial. Although, in retrospect, there may have been many errors and a good deal of prejudice in the trial itself, the professionalism and objectiveness of Arthur Koehler still stand as an example of science at its best in the service of the law….

Acknowledgment

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Figure 1 The ladder used in the kidnapping of the Lindbergh baby.

Figure 2 Detail of a cutter head illustrating how a defect allowed the number of knives to be determined.

Figure 3 Comparison of knife marks from mill planer on edges of 1- × 4-inch pine from two shipments from the Dorn mill and a ladder rail.

Figure 4 Comparison of knife marks on upper surface of ladder rail and North Carolina pine board located in shipment to the National Lumber and Millwork Company.

Figure 5 Comparison of defect marks in Hauptmann's hand-plane with marks on cleats (runs) from the ladder.

Figure 6 Rail 16 fitted into its original position in Hauptmann's attic.

Figure 7 Composite photograph by Koehler showing comparison of end grain (growth rings) in board from attic and rail 16.

Figure 8 Construction by Koehler showing probable grain pattern of missing piece between attic board and rail 16.

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Virtual Image

An image that cannot be seen directly. It can be seen only by a viewer looking through a lens.

Real Image

An image formed by the actual convergence of light rays on a screen.

Objective Lens

The lower lens of a microscope, which is positioned directly over the specimen.

Eyepiece Lens

The lens of a microscope into which the viewer looks; same as the ocular lens.

Transmitted Illumination

Light that passes up from the condenser and through the specimen.

Vertical or Reflected Illumination

Illumination of a specimen from above; in microscopy it is used to examine opaque specimens.

Condenser

The lens system under the microscope stage that focuses light onto the specimen.

Parfocal

Describes a microscope such that when an image is focused with one objective in position, the other objective can be rotated into place and the field will remain in focus.

Monocular

Describes a microscope with one eyepiece.

Binocular

Describes a microscope with two eyepieces.

Field of View

The area of the specimen that can be seen after it is magnified.

Depth of Focus

The thickness of a specimen that is entirely in focus under a microscope.

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Figure 7–1 The passage of light through a lens, showing how magnification is obtained.

Figure 7–2 The principle of the compound microscope. The passage of light through two lenses forms the virtual image of the object seen by the eye.

Figure 7–3(a) Parts of the compound microscope: (1) base, (2) arm, (3) stage, (4) body tube, (5) coarse adjust, (6) fine adjust, (7) illuminator, (8) condenser, (9) objective lens, and (10) eyepiece lens. *Courtesy Leica Microsystems, Buffalo, N.Y., www.leica-microsystems.com*

Figure 7–3(b) Optics of the compound microscope. *Courtesy Leica Microsystems, Buffalo, N.Y., www.leica-microsystems.com*

Figure 7–4 The comparison microscope—two independent objective lenses joined together by an optical bridge. *Courtesy Leica Microsystems*

Figure 7–5 Photomicrograph taken through a comparison microscope. On the right are the striation markings on the test-fired bullet, fired through the suspect weapon. On the left are the markings of the crime-scene bullet. *Courtesy Getty Images Inc.—Hulton Archive*

Figure 7–6 A stereoscopic microscope. *Courtesy of Mikael Karlsson, Arresting Images*

Figure 7–7 Schematic diagram of a stereoscopic microscope. This microscope is actually two separate monocular microscopes, each with its own set of lenses except for the lowest objective lens, which is common to both microscopes.

Figure 7–8 Polarization of light.

Figure 7–9 A visible-light microspectrophotometer. *Courtesy Craig Technologies Inc., Altadena, Calif., www.microspectra.com*

Figure 7–10 Two $50 bills are shown at top; one is genuine and the other is counterfeit. Below each bill is a microphotograph of an inked line present on each bill. Each line was ex-

amined under a visible-light microspectrophotometer. As shown, the visible absorption spectrum of each line is readily differentiated, thus allowing the examiner to distinguish a counterfeit bill from genuine currency. *Courtesy Peter W. Pfefferli, forensic scientist, Lausanne, Switzerland*

Figure 7–11 A scanning electron microscope. *Courtesy Jeol USA Inc., Peabody, Mass., www.jeolusa.com*

Figure 7–12 The cystolithic hairs of the marijuana leaf, as viewed with a scanning electron microscope (800×). *Courtesy Jeff Albright*

Figure 7–13 The melted ends of a hot filament break indicate that the headlights were on when an accident occurred. *Courtesy Jeol USA Inc., Peabody, Mass., www.jeolusa.com*

Figure 7–14 The sharp ends of a cold filament break indicate that the headlights were off when an accident occurred. *Courtesy Jeol USA Inc., Peabody, Mass., www.jeolusa.com*

Figure 7–15 A schematic diagram of a scanning electron microscope displaying the image of a gunshot residue particle. Simultaneously, an X-ray analyzer detects and displays X-ray emissions from the elements lead (Pb), antimony (Sb), and barium (Ba) present in the particle. *Courtesy Aerospace Corp., El Segundo, Calif.*