Proceedings of
a Symposium
at the J. Paul
Getty Museum,
April 1995

PROCEEDINGS

The Structural Conservation of Panel Paintings

The Getty Conservation Institute

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Proceedings of a symposium at the
J. Paul Getty Museum

24–28 April 1995

Edited by Kathleen Dardes and Andrea Rothe

THE GETTY CONSERVATION INSTITUTE
LOS ANGELES

Front cover: Alessandro Allori, *The Abduction of Proserpine,* 1570. Detail. Oil on panel, 228.5 × 348 cm. The J. Paul Getty Museum (73.PB.73), Los Angeles.

Back cover and page 305: Girolamo di Benvenuto, *Nativity,* ca. 1500, reverse. Tempera on panel, 204 × 161 cm. The J. Paul Getty Museum (54.PB.10), Los Angeles. The panel bears witness to the history of its conservation: This light, modern cradle was installed in 1987, after the removal of heavy, traditional crossbars (see page 187), traces of which are still evident. Strips of aged poplar, inserted to repair cracks caused by earlier restorations, can also be seen.

Page 1: Transverse surfaces of chestnut (*Castanea* sp.) (left) and poplar (*Populus* sp.) (right), showing pore structures.

Page 109: Illustration showing sawyers producing veneers; from J. A. Roubo, *L'art du menuisier* (Paris: Académie Royale des Sciences, 1769).

Page 187: Girolamo di Benvenuto, *Nativity,* reverse. A cumbersome, traditional cradle, installed around 1900 and removed in 1987, is shown.

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Foreword

In April 1995 the Getty Conservation Institute and the J. Paul Getty Museum sponsored an international symposium, "The Structural Conservation of Panel Paintings," at the J. Paul Getty Museum in Malibu, California. Initially the idea of Andrea Rothe, head of Paintings Conservation at the Museum, and enthusiastically supported by Kathleen Dardes, senior coordinator in the Institute's Training Program, the conference was attended by more than two hundred participants from some twenty countries, who gathered for five days of papers and discussions.

During pauses, participants were able to meet informally with old and new colleagues in the galleries and gardens of the Museum. This combination of formal and informal exchanges greatly encouraged the flow of ideas and contributed significantly to the success of the symposium.

The purpose of the symposium was to document the techniques, both traditional and contemporary, of panel stabilization. This book encompasses the wide range of topics covered by the speakers. After an introductory examination of wood characteristics, the papers go on to consider the technological aspects of wood, the history of panel-making techniques, and the various methods of panel stabilization that have been developed and refined over the course of many centuries. Indeed, as the reader will discover, many of the techniques described are the products of a long and venerable tradition developed by generations of master artisans, who then passed along an understanding of and sensitivity to the properties of wood. Other articles focus on the modern scientific and technical advances that conservation has made in the second half of the twentieth century—advances that have helped conservators solve, often by innovative methods, the most challenging structural problems.

In sponsoring this symposium, the Museum and the Conservation Institute hoped to contribute to a wider understanding of the historical, practical, and scientific aspects of panel stabilization. We are grateful to Andrea Rothe and Kathleen Dardes for the dedication they have shown in the organization of the symposium and in the publication of these proceedings.

Miguel Angel Corzo	John Walsh
DIRECTOR	DIRECTOR
The Getty Conservation Institute	The J. Paul Getty Museum

Preface

In addition to representing the aesthetic and intellectual sensibilities of their creators, the world's great paintings serve as rich historical documents. The close contact with these works of art that conservators and curators have long enjoyed allows access to their most hidden parts and, consequently, to a better understanding of the materials and working practices that are the underpinnings of artistic expression. For paintings are more than the manifestation of an idea or a creative impulse; they are also a composite of ordinary materials, such as wood, glue, canvas, metal, and pigments of various sorts, that have been put to a wonderful purpose.

Wood has served for centuries as a support for painting, largely because of its strength and availability. Paralleling the long history of wood as a painting substrate is an almost equally long history of attempts to control its behavior. An early recognition of the tendency of all wood species to deform under certain conditions has led generations of woodworkers to devise techniques, both varied and ingenious, to control the movement of wooden supports and its consequent damage to the paint layer.

However, even the most ingenious efforts on the part of panel makers to create strong painting supports were often overcome by the inherent properties of wood. In response to such problems, time has witnessed the development of various approaches—some now considered quite radical and intrusive—to the treatment of structural problems in panel paintings. Nowadays a more restrained approach is taken, informed by the ethical principles that guide the conservation profession, as well as by both the scientific knowledge and the tradition of craftsmanship that continue to nourish it.

It is important to understand the changes in thinking and practice that mark the evolution in the structural conservation of panel paintings. Many people skilled in the craft and traditions of panel repair and stabilization, however, have encountered few opportunities to pass their methods on to others beyond their immediate circle. Without a serious effort to document and present these methods to a wide professional audience, many of these approaches to the structural conservation of panels, and the rationales behind them, would be lost forever.

One of the editors of this publication, Andrea Rothe, recognized the need to make this type of information more accessible. This realization led to a series of discussions by staff of the J. Paul Getty Museum and the Getty Conservation Institute on how to bring to the attention of a wider audience the various working philosophies and methods, both traditional and contemporary, that have been used for the stabilization of painted panels. Working with an advisory group of experienced panel painting conservators from institutions in the United States and Europe, the Museum and the Institute developed the idea of an international meeting that would address a number of key topic areas of importance to a comprehensive treatment of this subject. These areas included aspects of wood science and technology relevant to wooden painting supports, historical methods of panel fabrication, and both historical and present-day approaches to the structural stabilization of panel paintings. The advisory group then identified the specialists best qualified to address these areas, including a number of craftspeople with long experience in panel conservation. Since many of these people had but infrequent opportunities to publish the results of their work or to participate in international conferences, their methods and techniques were not always known beyond their own workshops. It was the skills and accomplishments of these professionals that the symposium particularly wanted to document. We also wanted to afford these experts an opportunity for professional exchange with colleagues who had similar backgrounds and interests.

This symposium, therefore, was the first international gathering devoted specifically to the structural stabilization of panel paintings. Throughout the five days of the meeting, many different perspectives were presented and discussed. Some reflected the traditional, time-honored aspects of the panel conservation craft, while others were indicative of the scientific and technical strides panel conservation has made in recent years. It became clear to those attending the symposium that the modern conservator of panel paintings has at his or her disposal an expanding body of information and experience that melds traditional techniques, art-historical research, and scientific discovery.

The symposium set out to present the state of the art of the structural conservation of panel paintings. This volume, containing the contributions of the symposium's speakers, achieves our aim of making this information available to a wide audience of professional colleagues. We hope that it will also inspire further research and practical innovation in this area.

In addition to thanking the authors for their efforts with respect to both the symposium and this volume, the editors also would like to thank their colleagues at the J. Paul Getty Museum and the Getty Conservation Institute, most especially John Walsh, director of the Museum, and Miguel Angel Corzo, director of the Institute, both of whom have enthusiastically supported the goals of this project. Marta de la Torre, director of the Institute's Training Program, committed the program to the development of this project throughout its many phases, while Deborah Gribbon, associate director and chief curator at the Museum, supported the participation of the Museum's conservation and logistical staff. In addition, we would like to acknowledge the special contributions of Brian Considine, Valerie Dorge, Gordon Hanlon, and Mark Leonard. Sheri Saperstein assisted in the coordination of both the symposium and this volume with her customary flair, charm, and good humor.

The advice and guidance offered throughout the planning stages of the symposium by George Bisacca of the Metropolitan Museum of Art, New York; David Bomford of the National Gallery, London; and Ian McClure of the Hamilton Kerr Institute, Cambridge, are also reflected in these proceedings. For their assistance, we are very grateful.

In addition to the above, a number of other people lent their expertise as reviewers. These include Joseph Fronek, Los Angeles County Museum of Art; David Grattan and Gregory Young, Canadian Conservation Institute; Bruce Hoadley, Department of Forestry and Wildlife Management, University of Massachusetts, Amherst; Robert Krahmer, College of Forestry, Oregon State University; Paolo Mora, former chief restorer at the Istituto Centrale del Restauro, Rome; James T. Rice, Daniel B. Warnell School of Forest Resources, University of Georgia; Wayne Wilcox, Forest Products Laboratory, University of California.

Finally, we would like to thank Neville Agnew, associate director, programs, at the Getty Conservation Institute, for overseeing the various stages of the publication of this volume. Very special thanks are extended to the volume's managing editor, Tevvy Ball, whose fine eye and sure touch succeeded in taming a sometimes unruly manuscript. In this he was assisted by Sylvia Tidwell, who skillfully and scrupulously copyedited the manuscript; Elizabeth Maggio, Barbara Harshav, and Michelle Buchholtz, who assisted with translations from Italian and French; and Joy Hartnett, Scott Patrick Wagner, and Kimberly Kostas, who helped attend to the myriad details involved in preparing these proceedings for publication.

Kathleen Dardes
The Getty Conservation Institute

Andrea Rothe
The J. Paul Getty Museum

Introduction: Keynote Address

David Bomford

This symposium on the conservation of panel paintings, organized by the J. Paul Getty Museum and the Getty Conservation Institute, has created the conditions for one of those rare, defining moments in paintings conservation that are not always apparent at the time they occur. With a meeting and publication such as this, our disparate and far-flung profession has stopped for a moment, reflected on its contexts, its motives, and its actions, and then stepped forward with more unity and a better collective understanding.

At the last major conference to consider the treatment of panel paintings—the 1978 International Institute for Conservation congress "The Conservation of Wood in Painting and the Decorative Arts," held in Oxford—about one-third of the papers presented were on the theme of panel paintings. For the record, four of the speakers at that conference also have articles in the present volume.

Although the Oxford conference is often cited as the natural predecessor of this symposium, I have been reflecting more on a different week, in 1974, when the Conference on Comparative Lining Techniques took place in Greenwich, England. This was, without doubt, a key moment for our profession, as agreed by all who attended. For the first time, the history, ethics, and practice of the structural treatment of easel paintings (albeit on canvas) were debated in a straightforward and scholarly manner. After Greenwich, treatments could no longer be mysterious, unfathomable rituals rooted in the past. Traditional methods and craft-based skills still served as the basis of much good practice, but now these methods and skills had to be rational, explicable, and accountable. More important, the old automatism—the repeated major treatment of paintings for no other reason than habit—was no longer acceptable. In a brilliant keynote paper—still one of the wisest ever written about paintings conservation—Westby Percival-Prescott, the organizer of the Greenwich conference, spoke of the lining cycle—the relentless spiral of ever-increasing treatment and deterioration into which paintings can all too easily fall. He pointed out something so daringly radical, so threatening to all our livelihoods, that it produced a palpable sense of shock: *to do nothing* is often the best form of treatment. Today, when the notion of preventive conservation is taken for granted and advocating minimal intervention is common, when unlined paintings and untouched panels are prized beyond measure, it is difficult to recall just how often we intervened, even in the early 1970s.

The Greenwich conference was a landmark. It changed attitudes and set in motion a whole new rationalization for the treatment of paintings, establishing the policy that minimal treatment is best. It is also interesting to note that although a few of the authors in the present volume attended the Greenwich conference, only one actually presented a paper: this author is Andrea Rothe, who also delivered a paper at Oxford and whose original idea for a panel-conservation workshop resulted in this symposium and this proceedings volume.

Let us try to contextualize our theme of the structural conservation of panel paintings. During this symposium we shall be asking questions, considering choices, and describing actions. I shall begin by posing a simple puzzle to you: Let us say I have two groups of world-famous paintings. In the first is Titian's *Assunta* in the Frari, Botticelli's *Primavera* in the Uffizi, and Rubens's *Samson and Delilah* in the National Gallery, London. In the second group is Titian's *Pesaro Altarpiece,* also in the Frari; Botticelli's *Birth of Venus,* also in the Uffizi; and Rubens's *Garden of Love* in the Prado. What is the difference between these two groups?

Given the context of this symposium, the answer appears fairly obvious: the first group are all on panel, the second on canvas. But if we had asked the question at random of art historians or conservators not necessarily preoccupied with our subject, I imagine they might struggle for an answer and even then not be certain of all the facts. If we then produce another group of famous paintings—Raphael's *Foligno Madonna* in the Vatican, Leonardo's *Virgin of the Rocks* in the Louvre, and Pontormo's *Cosimo de' Medici* in the J. Paul Getty Museum—and ask what distinguishes them from the other two groups, the art historians and conservators might well be further confused—for these are all paintings originally on panel, now transferred to canvas.

Few individuals think about or are even aware of the structural basis of paintings. This lack of awareness of physical structure has serious implications for the few of us who take responsibility for these matters. A disregard for the nature of painting supports leads inevitably to a disregard for their importance or condition. Because practically no one monitors the versos of paintings, the responsibility for establishing guidelines for sound practice and observing those guidelines falls to us. It is inconceivable that the excesses of the early nineteenth century could ever be repeated—we only have to think of some four hundred Renaissance panels pointlessly transferred to canvas in St. Petersburg to realize the scale of it all—but it is incumbent on us to reach the same conclusions as those who met in Greenwich in 1974: our actions, great or small, must be logical, accountable, and ethical, bequeathing an honorable and defensible legacy to those who will care for paintings in the future.

I have mentioned that we are going to consider choices during this symposium. The papers at this symposium are loosely arranged in historical progression, beginning with the nature of materials and the making of panel paintings. Therefore, the first choices that we must consider are those facing the painters themselves. In general, the earlier panel painters operated within traditions that almost totally circumscribed their methods and materials. Perhaps because they were not aware of choice in the way that we now interpret the concept, they left few remarks to guide us. Nevertheless, there is much that can be learned from documentary sources and from examination of the works themselves that can inform us about the manner of their making.

Wood is, of course, an ideal material for movable paintings and altarpieces. It is strong, relatively light, and self-supporting. It can be planed smooth or carved in relief, and it is equally appropriate for the simplest of panels or the most fantastic of carved structures. Its resilience and autonomous strength can also be considered a long-term *disadvantage,* however, since both strengths allowed later predatory collectors to dismember great works into smaller, freestanding parts, beginning the process by which panel paintings have been scattered randomly and out of context in collections around the world.

Much recent technical research on early Italian altarpieces and other panel paintings has concentrated on reassembling (on paper, at least) the original sequences of now-separated fragments, such as those of Ugolino di Nerio's Santa Croce altarpiece, which are dispersed among collections in Berlin, London, and Los Angeles. The very nature of wood can be vital in this quest, as horizontal predelle and vertical registers of the great altarpieces were often painted on single, massive planks. To anyone who has bothered to look at the backs of such altarpieces in situ, this is a simple and obvious fact. However, only in relatively recent years have X rays been used to clarify the original structure of dismembered altarpieces by following wood-grain patterns through rows or columns of separated sections. X rays make it possible to reconstruct the widely scattered fragments of Ugolino's altarpiece into seven separate vertical units, each based on a massive poplar plank. The wood grain in these reassembled planks runs continuously from the tops of the pinnacle panels to the bases of the three-quarter-length saints. The predella, now separated into seven separate panel paintings, consisted of an enormous plank more than 4 m long.

X rays and visual examination also reveal the presence of irregularly spaced dowel holes down the sides of the seven vertical tiers; the holes—which only match up if the panels are correctly arranged—were clearly used to link adjacent planks. Faint batten marks on the backs of many of the panels indicate an original structural framework that supported the entire altarpiece. A stepped, or half-lap, shape at the side of each vertical plank suggests that the makers created the altarpiece so that it could be executed in separate sections and assembled in situ by pegging the planks and overlapping battens together. Remaining pieces of metal fixings on each vertical tier indicate the previous use of an overall metal strut to support the whole structure.

Deductions such as these, which bring to life the working methods of late medieval artisans, are vital if we are to understand works of art in context. These lines of research demand from each conservator of panel paintings that each join, hole, notch, nail, or mark on the backs and sides of panels, whatever its period or origin, be scrupulously preserved and recorded for the sake of future scholarship. As part of this symposium, conservators discuss the ethics of thinning panels and applying secondary supports—procedures that have, in the past, concealed or destroyed important evidence. Let us be sure in the future that not a single clue to the original structures of panel paintings is lost or concealed without adequate documentation.

Documentary evidence from the great ages of European panel painting—from medieval times to the Baroque—is somewhat sketchy. Some documentation is marvelously complete, such as the contract for a polyptych painted in 1320 by Pietro Lorenzetti for Santa Maria della Pieve in Arezzo, in which everything, from the subject to the materials and the structure, is precisely detailed. Other documents give us a brilliant, anecdotal immediacy, such as the financial accounts for Jacopo di Cione's San Pier Maggiore altarpiece (National Gallery, London) of 1370–71, in which the prices for the nails, eggs, pots, pigments, and gold are listed individually. This documentation even includes an entry that notes the charge for "taking and fetching the altarpiece to and from Santa Maria Nuova when it has been varnished." This record provides one of the few references in early Italian sources to the varnishing of painted altarpieces.

One of the most evocative of all documentary discoveries occurred in 1968, when some accounts were found in the state archive in Florence that provided information about the arrival in Florence of Hugo van der Goes's Portinari Altarpiece, the date of which had never been known for certain. These accounts detail the transport of the triptych by sea from Bruges via Sicily to Pisa, and then along the Arno to Florence, where it arrived at the San Frediano Gate on 28 May 1483. The documentation provides a vivid impression of the sheer size of the triptych and the physical difficulty of handling it: sixteen men were required to move it to its destination on the high altar of the Church of Sant'Egidio in the hospital of Santa Maria Nuova, where it was regarded as a marvel by all who saw it (it is now in the Uffizi). There is, incidentally, a technical curiosity about the portrait of the donor Tommaso Portinari on the left wing of the altarpiece. X rays reveal that it was painted separately on a sheet of tinfoil or parchment, which was then glued to the panel. Portinari left the Netherlands for Italy in 1477, before van der Goes had begun the wings of the triptych; apparently van der Goes insisted on painting a live study of his patron before Portinari's departure for Italy—and then incorporated the portrait into the triptych later.

Most documents are either of a legalistic or financial nature, or consist of practical treatises on the procedures of painting. Painting on wood at this period was the norm; there was little choice available. When wood as a material is mentioned at all, it is simply in terms of how to prepare it for painting. These documents occasionally mention the problems of wood—such as moisture, knots, and protruding nails—but the character of wood is seldom mentioned. Cennino Cennini is almost unique in referring specifically to different woods for different purposes. He recorded the use of poplar, linden, and willow for ancone or panels; boxwood for little drawing panels; maple or chestnut for brush handles; birch for drawing styluses; and nut, pear, or plum wood for boards on which to cut metal foil.

In general, though, available documentation provides meager information about painters' views of the wide variety of woods used for painting supports, or their attitudes toward the material qualities they exploited in making their art. Clearly, wood fulfilled many of the painters' requirements through its versatility as a medium—but was it the servant or the master of those who used it?

Such documentation does little to solve one of the recurring paradoxes of the history of painting materials: Did painters simply choose materials that fitted their perceived objectives, or did the nature of the materials themselves dictate the directions in which works of art developed? The safe answer suggests that the two notions are inextricably interdependent, although there are certainly moments in the history of art when the emergence or reassessment of materials seems to have determined subsequent aesthetic directions. Two such cases are the refined use of drying oils for painting in early-fifteenth-century Flanders, exploited by the predecessors of van der Goes, and the dependence of Impressionism on the new nineteenth-century pigments.

Perhaps the most famous myth of the whole technical history of painting involves the first of these two examples and a panel painting. Vasari wrote in his biography of Antonello da Messina of an occasion on which Giovanni da Bruggia (now known as Jan van Eyck) devoted the utmost pains to painting a picture and finished it with great care: "He varnished it and put it in the sun to dry, as was then customary. Whether the heat was excessive or the wood badly joined or ill-seasoned, the picture unfortunately split at the joints." Following this experience, van Eyck set about finding a paint medium that would dry in the shade, without the need of the sun, and that would be lustrous without any varnish. Hence he invented oil painting. "Enchanted with this discovery, as well he might be," Vasari continues, "Giovanni began a large number of works, filling the whole country with them, to the infinite delight of the people and immense profit to himself." The fact that this highly improbable legend is demonstrably untrue does not make it any less enjoyable, nor does it invalidate the premise that the material history of art and the connoisseur's history of art are closely intertwined.

The history of painting contains specific examples where the nature and limitations of painting on panel have affected the arrangement of a composition or, conversely, where the composition has dictated the structure of the panel. It is well known that painters avoided painting key components (such as faces) over panel joins, which risked coming apart. It is surely no coincidence that the faces of Holbein's two *Ambassadors* (National Gallery, London), recently restored, are carefully placed more or less centrally on two of the ten oak planks that compose the panel.

The artist's decision to paint on a panel becomes significant when there is a genuine choice to be made. From the later fifteenth century onward—and more rapidly in Italy than in northern Europe—convention increasingly allowed canvas paintings to have equal status with panel paintings. Consequently, convenience and lower cost led to greater use of canvas, especially for larger works. Many painters, however, used both canvas and wood. One of the great questions of the history of painting techniques is this: Why does a painter choose one support over another for a particular work? Why, for example, did Botticelli paint the *Primavera* on panel and the *Birth of Venus* on canvas? The works were probably both part of the same decorative scheme. Before the top of the *Birth of Venus* was cut, the works would have been the same size as each other—and also the same size as another work on canvas, *Pallas and the Centaur* (Uffizi Gallery, Florence). Botticelli painted the *Primavera* just before he left for Rome in 1481 or 1482, and he painted the two canvases just after he returned to Florence. Had he somehow been influenced in favor of canvas while he was away working in the Sistine Chapel? If so, he certainly reverted to panel after these two pieces, and continued to use panel for the great majority of his work.

We can ask the same question with regard to many painters over the next two centuries. While the answers would vary, the majority of choices would be, undoubtedly, pragmatic. We must never overlook practical or commonsense explanations for the ways in which painters worked or for the constraints of tradition within which they learned their craft.

Rubens and Rembrandt, for example, were equally versatile on wood and canvas, although they operated within a tradition that had hitherto favored wood for painting supports. In his Leiden and early Amsterdam periods, Rembrandt worked almost exclusively on wood, producing those beautifully wrought, surprisingly colorful small panels that established his reputation as a *fijnschilder* (fine painter). He continued to use panels throughout his career, but with the production of larger portraits and history pieces in the early 1630s, he increasingly chose canvas. This choice can be easily explained by practical or financial considerations. Apart from the existing tradition of using panels, they were easily available ready-made in a range of standard sizes from specialist panel makers. They were also much preferred for smaller-format pictures because they were self-supporting and needed only simple preparation. Since panels were more expensive than canvas, however, there came a point at which it was worthwhile to go to the greater trouble of stretching and priming canvas. In his down-to-earth discussion of the advantages of canvas in his *Inleyding tot de Hooge Schoole der Schilderkonst (Introduction to the High School of Painting),* Rembrandt's pupil Samuel van Hoogstraten wrote that canvas was "suited most for large paintings and, when well primed, easiest to transport."

Incidentally, while on the subject of seventeenth-century Dutch panels and of Rembrandt in particular, we must note the extraordinary success of dendrochronology (up through the seventeenth century) in clarifying dating problems. Tree ring analysis can also give spectacular confirmation that certain panels have come from the same tree. For example, *The Woman Taken in Adultery* of 1644 (National Gallery, London) and the *Portrait of Herman Doomer* of 1640 (Metropolitan Museum of Art, New York) have the same structure, as does the panel to which the 1634 canvas painting *Saint John the Baptist Preaching* (Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie) has been affixed—proof that the third painting was also done in Rembrandt's studio. Nor can the dendrochronologist ignore wider aspects of European history. Peter Klein recently reminded me of a long-forgotten war between Sweden and Poland in the late 1640s, which stopped forever the supply of Baltic oak to western Europe and established one of those key dates that every student of painting techniques should know.

Rubens's restless genius resulted in many extraordinary experimentations with his painting supports. He frequently enlarged his panels as he went along, in some cases doubling or tripling the original size with a bewildering patchwork of added pieces. In the *Watering Place* (National Gallery, London), composed of eleven pieces of wood, Rubens successively moved the position of the sun to the left as he extended the composition. The result is there are now three suns: two painted and one drawn. In other cases, the complexity of the structure is not the result of enlargement, since Rubens seems deliberately to have constructed composite panels that were then painted in a single campaign of working. The exquisite companion paintings of the *Château de Steen* (National Gallery, London) and *The Rainbow Landscape* (Wallace Collection, London), on twenty planks and nineteen planks, respectively, are examples of this method. Beyond simple enlargement, did Rubens have a purpose in constructing such elaborate panels? Did he believe that such construction might somehow make the work more stable? Was he simply using up scraps of wood? About half of Rubens's entire output of oil paintings, including his oil sketches, was on wood panel. He seems to have liked the smooth surfaces of panels prepared with white grounds. Only once in surviving documents do we read of this preference; in a letter to Sir Dudley Carleton in 1618, he wrote, "It is done on panel because small things are more successful on wood." In fact, the appeal of panel painting was so great for Rubens that he was quite undeterred by the considerable difficulties of constructing and painting on large panels. Rubens's remark anticipates the only other quote I have been able to find to explain a painter's preference for wood over canvas. Philippe de la Hyre, son of the more famous Laurent, said in a lecture in 1709, "Wood prepared for working is much smoother than canvases; that is why it is greatly to be preferred for smaller works which require great refinement."

Panel painting continued, of course, through the nineteenth century. Wood was still the most convenient material for smaller works. Countless oil sketches exist on little panels, of which the plein air paintings of the Barbizon school and Seurat's celebrated studies for the *Baignade* and the *Grande Jatte* are obvious examples.

In the nineteenth century—no doubt inspired by the increasing expertise of picture restorers in thinning and backing old panel paintings—painters continued to experiment with wooden panels. For example, many of the small genre pictures of Meissonier (a fascinating character who was Manet's commander in the Franco-Prussian War and also the sworn enemy of Courbet) were assembled from small, thin strips of either sycamore or oak, in arrangements reminiscent of Rubens's panels. So thin they are almost veneers, they are mounted on thin oak backboards. Is this simple enlargement a curious technical idiosyncrasy of Meissonier? In the case of the *Halt at an Inn,* now in the Wallace Collection, London, the evidence provides a satisfying proof of enlargement: The panel consists of nine members, the central part being sycamore; the rest of the members are oak mounted on an oak veneer backing. The original composition, comprising the center panel and the first four additions, was engraved by Flameng and signed and dated 1862. Meissonier then enlarged the composition to its present size, probably in 1863. He signed it at both stages—above the left-hand doorway in the central part, and at the bottom left on the final addition. Valuable documentary evidence of various types has elucidated the creation of this particular painting.

Once a panel painting left the artist's studio, it began its precarious existence in a world of unpredictability and danger. The misfortunes of paintings in the last half millennium are well known; it is miraculous that so many have survived. Wooden panel paintings are, of course, especially vulnerable, since their main structural element exists in a condition of predictable instability that is under control if the surroundings are benign but easily out of control should the surrounding environment change.

Wood is such a familiar material that it is easy to underestimate its abilities to behave unexpectedly. The simple fact is that we still do not fully understand the behavior of partially restrained, or even unrestrained, centuries-old wooden panels. While we understand the general idea of expansion and contraction in humid and dry conditions, the stresses and strains of a composite structure can be very complex. We cannot predict how a painted panel will behave if, for example, it is held for years in steady conditions and then exposed to slow or rapid cycles of change. What actually happens when a panel is moved from a dry climate, where it has been for centuries, to an air-conditioned museum? What is the impact on the painting? What limits of tolerance have already been breached? A great mistake of past generations of restorers was to assume they could ignore or override the natural tendency of wood to warp, twist, split, and rot. Many past treatments have tried to impose structural restrictions on panels without imposing corresponding control of the environment. The long-term results of cradling, cross-grain battens, and rigid frame fitting are clearly demonstrated—so, too, are the innumerable cases in which restorers have regarded the wood as a simple nuisance and have thinned panels to a wafer (a process that actually made them *more* troublesome) or jettisoned them altogether by transferring the paint to a new support.

As conservators we see examples of these attitudes each day of our working lives, and we must deal with the consequences. It is no use, however, to say, "Well, *I* wouldn't have started from here." All of the horrors, misjudgments, and merely careless acts have already occurred; we must start from what has resulted. Conservators of panel paintings must be empiricists above all else. Our starting point is a situation in which centuries of aging, neglect, and malpractice have transformed the condition of many panel paintings into something far removed from their original states. Our conservation options are limited by the situation, but there are still choices to be made in terms of prevention and intervention. These choices are explored in all their variety during this symposium.

In this volume we learn about the pros and cons of balsa backing, attached and unattached auxiliary supports, retention or cutting out of deteriorated areas, and reinforcement with battens and V-shaped wedges. We see traditional hand tools, used with consummate skill; ingenious clamping jigs; and state-of-the-art low-pressure systems. We also learn something of old regional practices that may cause us to reexamine our own understandings of the properties of wood. One such example is the so-called Munich treatment, in which shellac in alcohol is copiously brushed onto the backs of warped panels to reduce their curvature. Clearly the shellac must be acting as more than a simple moisture barrier. The question raised by the Munich treatment opens up a whole realm of study of the effects of solvents other than water on wood.

We are privileged to be witnesses as the world's leading practitioners of the conservation of panel paintings question one another, debate choices, and describe actions. Here we learn in detail about the mistakes of the past, directions of the present, and speculations about the future.

We also explore unfamiliar corners of art history and the history of conservation, and touch, in passing, on the methodologies of historical inquiry. On this historiographical note, I must mention another famous legend concerning a panel painting ascribed to Michelangelo, the *Entombment* in the National Gallery, London. One of the abiding myths about this picture recounts that the painting was discovered in the nineteenth century doing duty as a market stall in Rome "for the sale of fish, frogs, etc. and old pans, gridirons etc. etc." The myth grew when, based on this story, Helmut Ruhemann, who cleaned the painting in 1968, explained the hundreds of little, raised, discolored spots on the surface of the picture as the excreta of flies attracted by the fish.

Recent scholarship has blown the legend apart. The brown spots are not flyspecks at all, but straightforward mold. And the story about the panel being used as a stall or tabletop becomes distinctly shaky when we trace it back to the Roman dealer who had the painting and discover that he used exactly the *same* story about at least one other panel by

Palmezzano that passed through his hands. My colleague Jill Dunkerton, who uncovered this diverting little piece of misinformation, commented in a lecture on the *Entombment*: "This recycling of battered old panel paintings as furniture was a little joke—frequently repeated, I fear—of the dealer, and yet another reminder of how careful we need to be in our assessment and interpretation of any piece of evidence about a painting, be it anecdotal, documentary, or scientific."

No mythology is necessary for my last example. Its bizarre history is apparent with even the most casual examination. It is the Trinity Altarpiece, begun by Pesellino and finished by Filippo Lippi, who delivered it in 1460 after Pesellino's death in 1457. A set of fascinating documents describes the commissioning of the altarpiece and what happened to it when it was left uncompleted on Pesellino's death. Having been assessed by Lippi and Domenico Veneziano as just half finished, it was taken from Florence to Prato for Lippi to complete. Meanwhile, a financial dispute was in progress between Pesellino's widow and his business partner, which complicated the final payments made to her for her husband's work on the painting. Which parts were by Pesellino and which by Lippi has been the subject of intense debate ever since the altarpiece was removed from the Church of the Compagnia dei Preti in Pistoia in the eighteenth century. At that time, the main panel was sawn into five fragments that, apart from the two angels, one might imagine to be so irregular in shape as to make them unsalable. Nevertheless, they were dispersed and sold. The *Crucifixion* fragment was purchased in 1863 by the National Gallery, London, which initiated a search for the other pieces. Three other fragments were found over the next sixty-five years. The fourth (the two saints on the left) was discovered in the British Royal Collection, which would not part with the piece but instead released it on loan in 1919 to be joined to the other parts. (In theory, if the altarpiece is ever moved or treated, the queen's restorer should be in attendance.) The bottom part of the right-hand pair of saints, who were found in 1929, never did surface, so a restorer was commissioned to paint their lower robes and feet.

The predella panels, also sawn apart in the eighteenth century, were bequeathed in 1937, seventy-four years after the reassembly of the jigsaw began. This complicated and generally unsatisfactory story has a recent and upbeat postscript. The predella—now assumed to be entirely by Filippo Lippi and his workshop rather than by Pesellino—has always been obviously too short for the main panel and original frame. Now the missing cental part of the predella has been identified as a panel by Filippo Lippi of the *Vision of Saint Augustine* in the Hermitage, St. Petersburg. Everybody knew the painting existed; some even remarked on its affinities with the Trinity Altarpiece; but until now, no one had suggested that it had been part of the same plank as the other predella panels.

This story represents the whole checkered history of panel painting in one example. It begins with a complicated genesis, documented with an extraordinary clarity that conjures up the immediacy of life and death, the stop and start of the painting process, and the realities of financial transactions and legal disputes. Next the painting enjoys an undisturbed existence for three centuries in Pistoia, followed by butchery and dispersal. Finally the artwork is painstakingly reassembled during the last two centuries (concurrent with current research on its original format), and it finally comes to rest in the relative tranquillity of a modern museum environment.

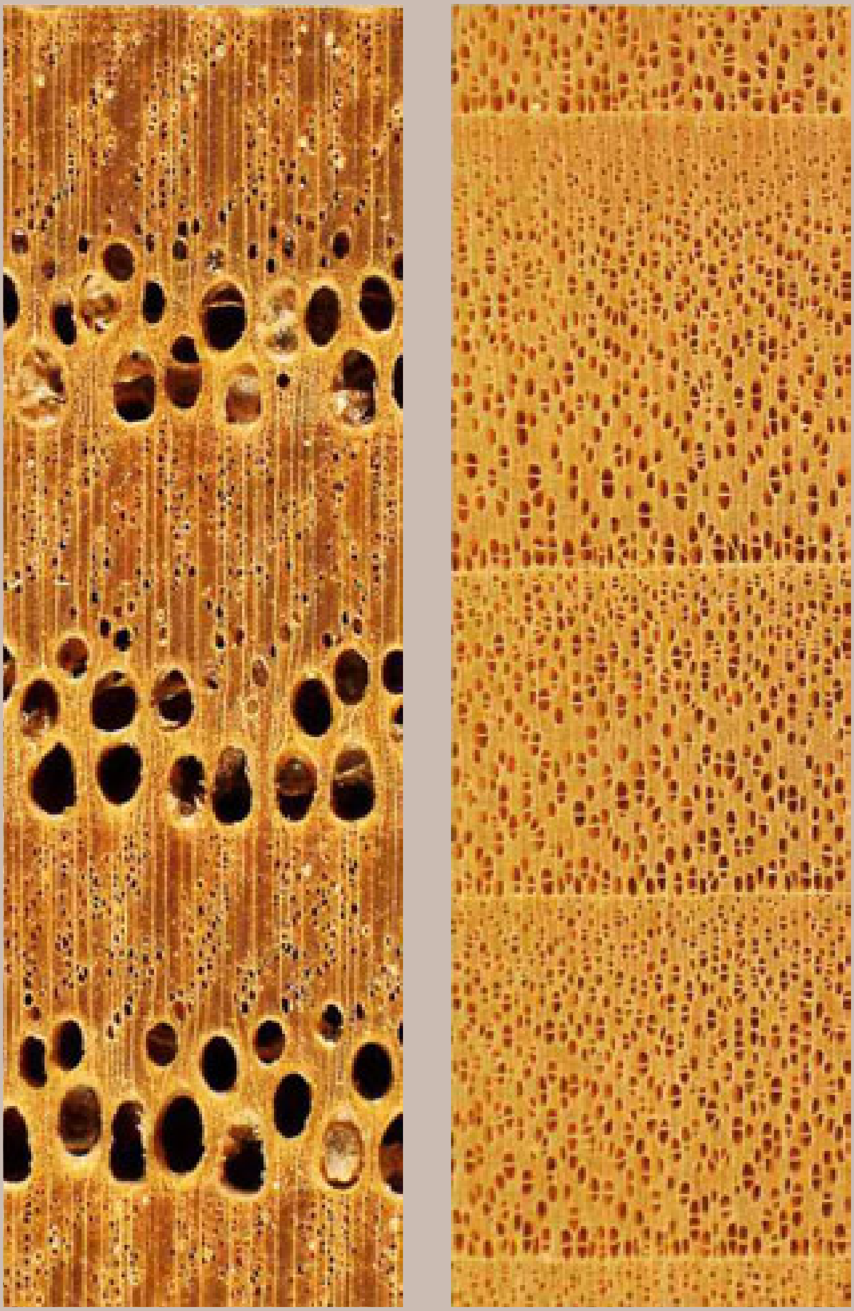
Panels are not simply the convenient carriers of the painter's invention. Panels *matter* in themselves, in the same way that canvases began to matter to us in Greenwich in 1974, and in the same way that documents, preparatory drawings, underdrawings, paint layers, inventories, and archives matter to us today. All of these materials contribute to a complete account of a work of art—from its commission, planning, preparation, execution, and delivery, to its ownership as a cherished possession, to its precarious survival, and, finally, to a present-day existence as cultural artifact, social record, and signifier of individual genius.

It is important to emphasize the totality of the work of art. While a painting may be a sublime creation of its maker's aesthetic sensibility, it is also a material document with a unique character given by the method of its making and the circumstances of its survival. When an artwork's history permits, its continuity over time can be thrilling. If we are lucky, we can appreciate a structure essentially unaltered since it left the artist's hand. It is our function as conservators to preserve, stabilize, consolidate, and repair where necessary—and it is also our responsibility to interrupt that continuity from the artist's hand as little as we possibly can.

The conservation of panel paintings must begin and end with the integrity of the historical object and the work of art. If we criticize, often justifiably, the failures of the past to address this requirement—as well as criticize the excessive interventions of our predecessors—then we must be accountable ourselves to the judgments of those who follow us. If we inform ourselves of all the historical contexts surrounding these works, if we ask the right questions, consider the best choices, and justify our actions, then the future of the panel paintings in our care should be assured.

PART ONE

Wood Science and Technology



Chemical and Physical Properties of Wood

R. Bruce Hoadley

From the beginning of civilization, wood has played an indispensable role in human survival. It is therefore not surprising that wood retains a prominent place in our cultural heritage. In the decorative arts wood has routinely been utilized because of its aesthetic virtues. In contrast, when wood is used for painting panels, where the surface appearance is obscured, the choice of wood reflects the universal availability of the resource as well as the working and performance properties of the timber. As an engineering material wood is strong and stiff for its weight and has density and hardness in the range suitable for conversion with hand tools. Wood is chemically stable when dry, and its surfaces offer a compatible substrate for paint application. The use of wood is not without its pitfalls, however, and requires the understanding that it is anisotropic—that is, it exhibits properties with different values when measured in different directions—as well as hygroscopic—adsorbing and releasing moisture readily. It is also dimensionally unstable and subject to deterioration by fungi and insects.

It is fundamental when exploring the complex nature of wood to remember that wood comes from trees and that usable timber is found in tens of thousands of tree species the world over. Pieces of wood large enough for painting panels are normally from the trunks or stems of mature trees. While many features of wood structure are common to all tree stems without regard to type of wood, it is not surprising that among such a diverse resource deriving from so many different species, a wide array of characteristics can be expected—such as the twelvefold variation in density from the lightest to the heaviest woods.

Trees are living plants, and wood is cellular tissue. Understanding wood therefore begins at the cellular level, and it is both appropriate and important to think of wood as a mass of cells. Woody cells evolved to satisfy the needs of trees—on the one hand to serve as good structural beams and columns, on the other hand to provide systems for conduction of sap and storage of food materials. The cells specialized for these mechanical and physiological functions are primarily elongated and fiberlike and parallel to the tree-stem axis. The alignment of these longitudinal cells in wood determines its grain direction. The stem of a tree "grows" in diameter by adding cylindrical layers of cells, which we recognize as growth rings. The combination of the axial direction of longitudinal cells and cell arrangement in growth rings gives wood tissue its anisotropy: its properties are significantly different in its three structural directions.

All timber species have common attributes of stem form and structure, and the fundamentals of wood properties can be discussed in general terms. Consideration of particular woods, however, reveals that certain groups or individual species require qualification. As a first level of investigation, for example, we recognize the broad differences between the hardwoods and the softwoods; more specifically, we recognize that one species of pine may be strikingly different from another. The systematic study of anatomy goes hand in hand with wood identification, and familiarity with anatomical structure is fundamental to the understanding of wood properties in general, as well as to the understanding of the important similarities and differences among woods.

Of the problems arising in painting conservation, those involving moisture-related dimensional change are certainly among the most challenging. Therefore, along with a brief review of pertinent chemical and mechanical properties of wood, this article will emphasize wood-moisture relationships, with particular reference to dimensional change.

Specific Gravity of Wood

Specific gravity—that is, relative density—is perhaps the single most meaningful indicator of other properties of wood. It is closely related to strength and surface hardness, as well as to resistance to tool action and fasteners. Woods of higher specific gravity generally shrink and swell more than woods of lower specific gravity, and they present greater problems in seasoning.

Specific gravity is the ratio of the density of a substance to the density of a standard (usually water). In reference to wood, it is customary to measure density on the basis of oven-dry weight and current volume. Because of shrinkage and swelling, the volume of wood may vary slightly with its moisture content. Density is expressed as weight per unit volume: as grams per cubic centimeter or as pounds per cubic foot. Water has a density of 1 g cm^{-3} (62.4 lb ft^{-3}). A sample of wood having a density of 0.5 g cm^{-3} (31.2 lb ft^{-3}) is half as heavy as water and has a specific gravity of 0.5. (Note that specific gravity is a unitless quantity.)

Among woods the world over, specific gravity ranges from less than 0.1 to greater than 1.0. Among the more familiar woods, balsa (*Ochroma* spp.) has an average specific gravity of 0.15; snakewood (*Piratinera guianensis*) averages 1.28. Figure 1 shows a comparison of specific gravity values for a number of woods, including those commonly found in painting panels. The chart shows that the terms *hardwood* and *softwood* are misleading with regard to literal hardness and softness. It is valuable to understand these contrasting terms as indicating botanical classification with reference to different anatomical structure rather than to disparate physical and mechanical properties.

Physical Structure of Wood

Many of the physical and mechanical properties of wood are inherently tied to its anatomical structure. Gross features of wood—that is, visual features or those apparent with low-power magnification such as a 10× hand lens—provide important indications of its properties. It is therefore appropriate to begin by highlighting the gross structure of wood.

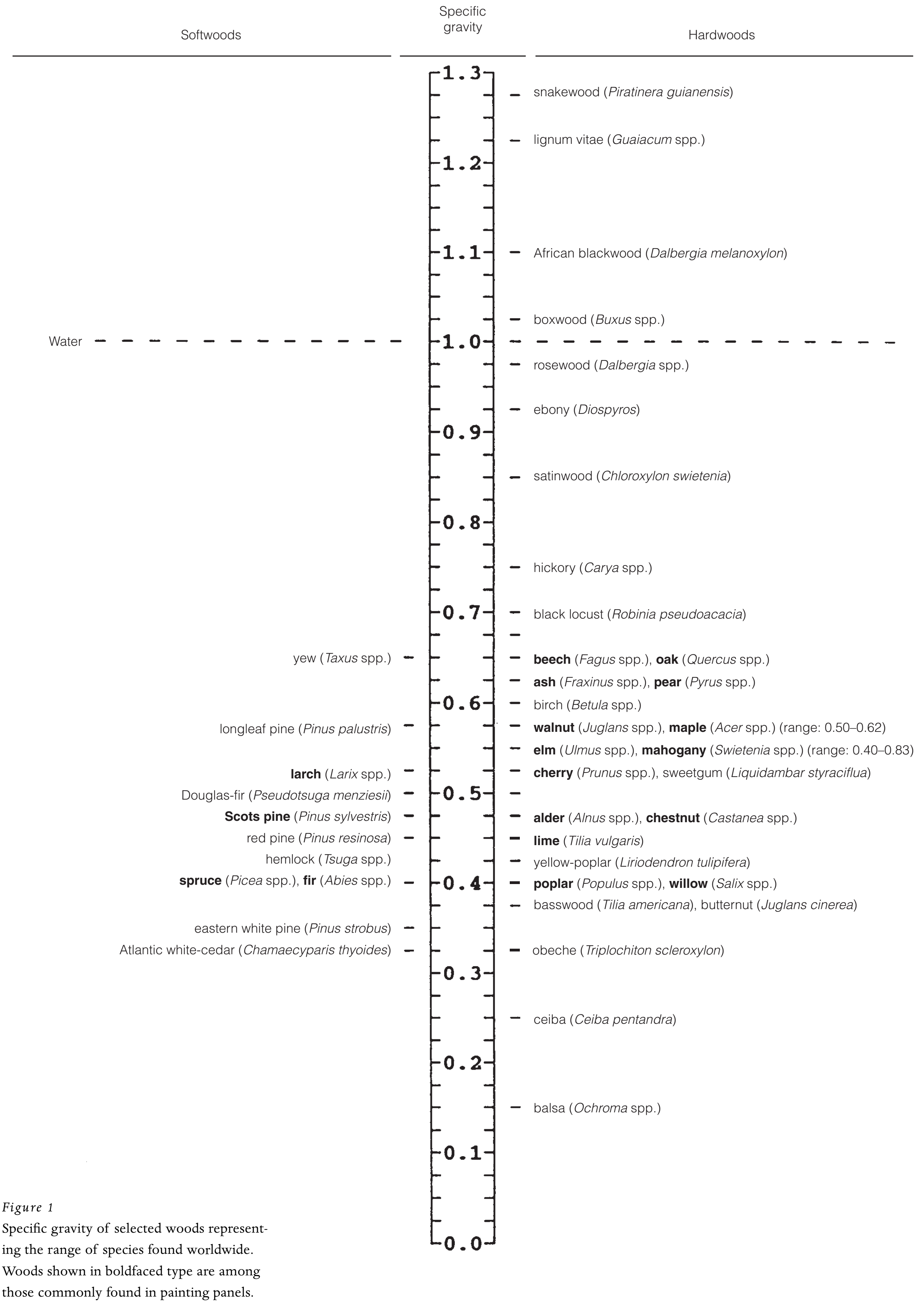


Figure 1
Specific gravity of selected woods representing the range of species found worldwide. Woods shown in boldfaced type are among those commonly found in painting panels.

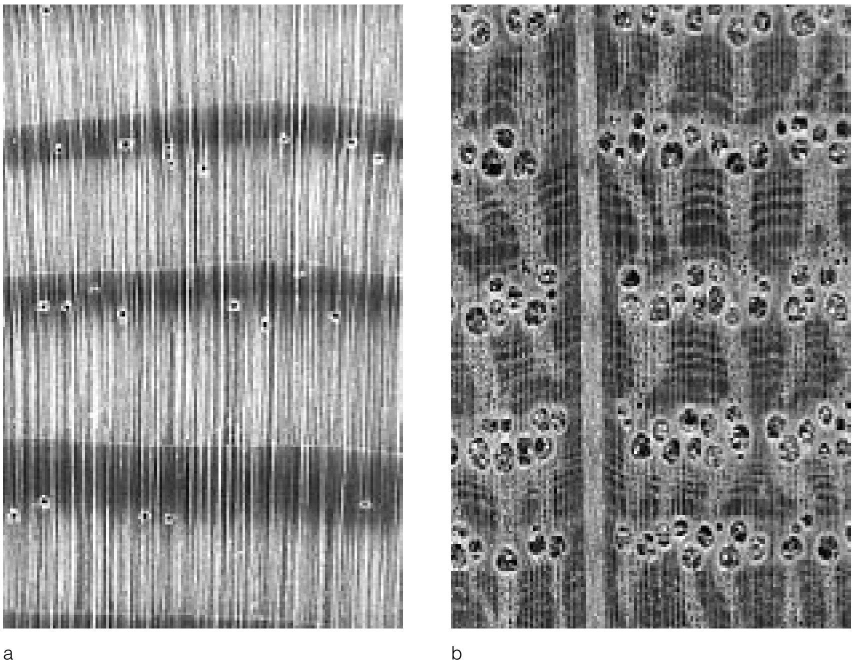


Figure 2a, b
Cross-sectional (end-grain) surfaces of (a) an uneven-grained softwood, Scots pine, and (b) a ring-porous hardwood, white oak, showing features visible with a hand lens (10× magnification).

Gross features

In viewing end-grain surfaces (Fig. 2a, b), individual wood cells usually cannot be seen without magnification. (In certain hardwood species, the largest cells, vessel elements, may be evident as visible pores on cleanly cut surfaces.) However, the familiar pattern of circular growth rings is apparent, concentrically arranged around the central pith. Within each ring, depending on the species, a first-formed earlywood layer may be distinct from an outer latewood layer. The visual pattern, or *figure,* on longitudinal board surfaces is most commonly the result of this earlywood-latewood variation. Distinct earlywood-latewood contrast usually indicates variation in cell characteristics, with latewood having greater density than earlywood. In some woods, however, there may be no significant difference in properties within growth rings.

Individual wood cells usually have an elongated shape, although they vary in proportions, from short and barrel shaped to long and needlelike. Most cells are longitudinal; that is, they are elongated vertically in the standing tree, parallel to the stem axis. On an end-grain surface we therefore see these cells in cross section. Scattered through the longitudinal wood cells are horizontally oriented ray cells, grouped to form flattened bands of tissue called *rays*. These ribbonlike rays (with their flattened sides oriented vertically) radiate horizontally outward from the pith, crossing perpendicularly through the growth rings. Individual ray cells are always too small to be seen without magnification, and therefore narrow rays are not apparent. However, some hardwood species have rays of up to tens of cells in width, which are therefore visible as distinct radial lines on cross sections. Collectively, the ray cells in most species account for less than 10% of the volume of the wood. It is important to understand that rays are present in every species and, whether visible or not, have an important role in many properties of wood.

The cylindrical form and arrangement of the growth rings in the tree stem, along with the vertical and horizontal arrangement of cells,

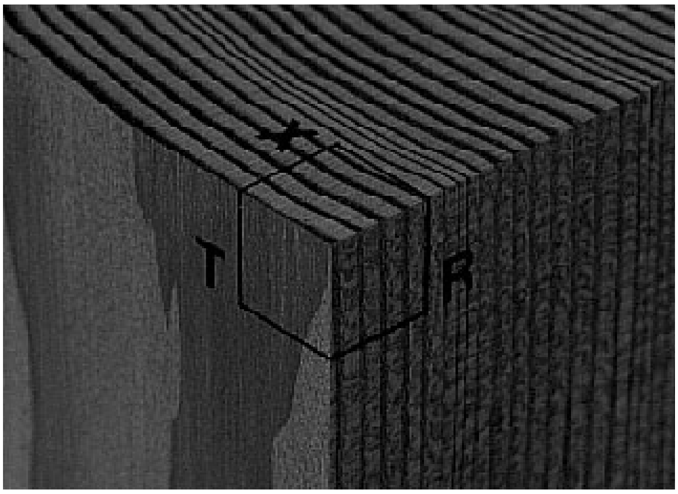


Figure 3
Block of coniferous wood, Douglas-fir, cut into a cube along the principal structural planes: transverse or cross-sectional (*X*), radial (*R*), and tangential (*T*).

establishes a three-dimensional orientation to the wood tissue (Fig. 3). A plane perpendicular to the stem axis is termed the *transverse plane,* or *cross-sectional plane,* also appropriately called the *end-grain surface,* as represented by the end of a log or board. The tree cross section is analogous to a circle, and a longitudinal plane passing through the pith of the stem (as would a radius of the circle) is a *radial plane* or surface. A plane parallel to the pith but not passing through it forms a tangent to the circular growth-ring structure at some point and is termed a *tangential plane* or surface, at least at that point. Relative to the anatomical structure of the wood, the tangential "plane" would take on the curvature of the growth ring. However, any slabbed log surface or "flat-sawn" board is accepted as a tangential cut, even if the board surface is truly tangential only in a limited central area. In a small cube of wood, as used for anatomical study, the curvature of the rings is insignificant, allowing the cube to be oriented to contain quite accurate transverse, radial, and tangential faces (Fig. 3).

Thin slices or sections of wood tissue, as commonly removed from the surfaces for study, are termed transverse, radial, and tangential sections. These tissue sections, as well as the planes they represent, are often designated simply by the letters *X, R,* and *T,* respectively.

In a further exploration of the anatomical nature of wood, generalities must give way to more specific detail according to the type of wood considered. A systematic approach is to follow the standard botanical classification of wood.

Within the plant kingdom, timber-producing trees are found in the division spermatophytes, the seed plants. Within this division are two classes, the gymnosperms and the angiosperms. Trees belonging to the gymnosperms (principally in the order Coniferales) are called *softwoods.* In the angiosperms, a subclass known as dicots (dicotyledonous plants) includes *hardwoods.*

Anatomical characteristics: Softwoods

The cell structure of softwoods is relatively simple compared to that of the hardwoods (Fig. 4a–c). Most of the cells found in coniferous woods are tracheids, which account for 90–95% of the volume of the wood. Tracheids are fiberlike cells with lengths of approximately one hundred times their diameters. Average tracheid lengths range from 2 mm to 6 mm among coniferous species, with a corresponding diameter range of approximately 20–60 μm. The relative diameter of tracheids is a basis for classifying texture among conifers. Tracheid size is important to the porosity and to the performance of coatings applied to wood.

Across a softwood growth ring, latewood is distinguished from earlywood by decreased radial diameter and increased cell-wall thickness. The transition may be gradual in some woods, abrupt in others. The earlywood-latewood contrast may be slight in some woods ("even-grained" woods) or may be pronounced in others ("uneven-grained" woods). In uneven-grained woods such as hard pines or larches, there may be as much as a threefold difference in specific gravity (0.3–0.9) from earlywood to latewood.

Some coniferous species have resin canals, tubular passageways lined with epithelial cells that exude resin, or pitch, into the canals. Resin canals are a constant feature of some genera in the family Pinaceae (the pine family), including *Pinus* (pine), *Picea* (spruce), and *Larix* (larch). Resin canals are largest and most numerous in the pines—they are usually distinct to the naked eye. In other species, magnification may be required to locate them. The resin from canals may bleed through paint films and result in yellowish speckling of finished surfaces. The rays in softwood are narrow, usually one cell wide (except occasional rays with horizontal resin canals in some species), and therefore cannot be seen without magnification. With a hand lens they are barely visible—appearing as light streaks across radial surfaces.

Anatomical characteristics: Hardwoods

In comparing the anatomy of the hardwoods with that of the softwoods, several general differences are apparent. There are many more cell types present in hardwoods, and there is more variation in their arrangement. Rays in hardwoods vary widely in size, from invisibly small to conspicuous to the eye. Temperate hardwoods lack normal resin canals.

Hardwoods have evolved specialized conductive cells called vessel elements, which are distinct in having relatively large diameters and thin cell walls. They occur in the wood in end-to-end series, and their end walls

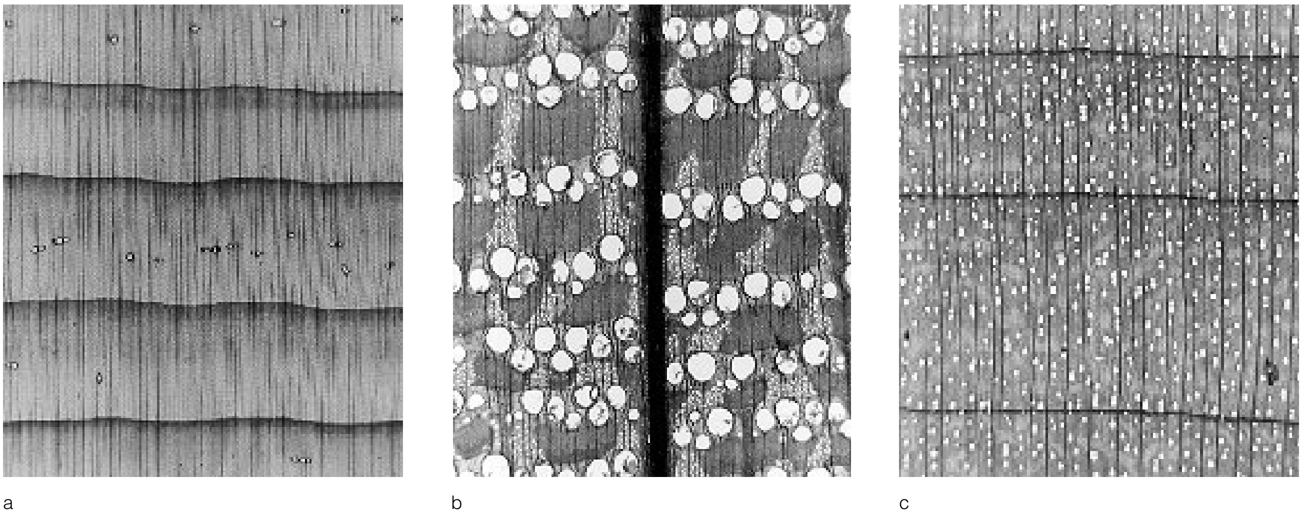

a
b
c

Figure 4a–c
Transverse sections of (a) a typical softwood, spruce; (b) a ring-porous hardwood, oak; and (c) a diffuse-porous hardwood, maple.

have disappeared; thus they form continuous vessels ideal for sap conduction. When vessels are cut transversely, the exposed open ends are referred to as *pores*. Pores vary in size among and within species. In certain woods such as chestnut and oak, the largest pores are up to 300 μm in diameter and can be easily seen without magnification, whereas in some species, such as holly, the pores are no larger than 40 μm in diameter and are barely perceptible even with a hand lens. Among hardwoods, pore size serves as a measure of texture. Oak has large pores and is coarse textured; pear has very small-diameter pores and is fine textured.

In some species (e.g., oaks, ashes, elms) the largest pores are concentrated in the earlywood. Such woods are said to be *ring porous;* they are inherently uneven grained and therefore have distinct growth-ring-related figure. Ring-porous structure results in uneven density and affects woodworking behavior with characteristics such as uneven resistance to abrasive paper or uneven retention of pigmented stains. In certain other woods (e.g., maple, birch, lime, poplar) pores are more uniform in size and evenly distributed across the growth ring; these are said to be *diffuse porous*. Such woods may show inconspicuous figure, or figure may be associated with uneven pigmentation or density of fiber mass in the outer latewood. Most diffuse-porous woods of the temperate regions have relatively small-diameter pores, but among tropical woods, some diffuse-porous woods (e.g., mahogany) have rather large pores. A third classification, *semi-ring-porous* (also called *semi-diffuse-porous*), refers to woods in which the first-formed pores in a growth ring are large, but the pores decrease in size gradually to small pores in the latewood, without clear delineation between earlywood and latewood.

Hardwoods have three other types of longitudinal cells: fibers, tracheids, and parenchyma cells. All are uniformly small in diameter (mostly in the range of 15–30 μm) and therefore can be seen individually only with microscopic magnification. Fibers are present in all woods and are characteristically long and needlelike, with tapering, pointed ends and relatively thick walls. On transverse surfaces, masses of fibers appear as the darkest areas of the tissue. Thick-walled fibers are characteristic of high-density woods such as oak and ash. Low-density hardwoods such as poplar have thin-walled fibers. Tracheids and parenchyma cells range from absent or sparse to fairly abundant. They are thinner-walled cells than are fibers, and when they are present in sufficient numbers, the resulting areas of tissue usually appear lighter in color than adjacent fiber masses.

Rays are quite variable among hardwood species. The size of rays is expressed by cell count as viewed microscopically on tangential sections, particularly ray width, or *seriation,* of the largest rays present. In woods such as chestnut and willow, the rays are *uniseriate* (that is, only one cell wide) and therefore visible only with a microscope. At the other extreme, such as oak, the largest rays are up to 40 seriate and up to several inches in height. Rays in oak are conspicuous to the unaided eye.

Rays influence physical and mechanical behavior as well. Rays, especially larger ones, represent planes of weakness in the wood. Shrinkage stresses associated with the seasoning of wood may develop separations, or checks, through the ray tissue. Also, the restraining effect of the rays results in differential radial and tangential shrinkage, a common cause of cupping in flat-sawn boards and of radial cracking in timbers.

Chemical Properties of Wood

Wood, as the biological product of higher-order plants, has a chemical composition that is understandably complex, and a thorough discussion of wood chemistry is quite beyond the scope of this article. However, even a brief summary of the more important fundamentals of cell-wall chemistry provides a basis of understanding of the anisotropic physical and mechanical properties of wood—especially its hygroscopic nature and dimensional behavior—and of chemical reactions involved in such practical conservation procedures as finishing, gluing, stabilization, and preservative treatment.

Chemical composition

The bulk of cell-wall substance is a composite of three major types of organic molecules: cellulose, hemicelluloses, and lignin. These constituents can be thought of as skeletal, matrix, and encrusting substances, respectively. Only minor amounts of inorganic (ash) content are present in wood. In various amounts, depending on species, additional substances called extractives, or extraneous materials, may also be present, mainly as additives to the heartwood.

The major chemical constituents of wood are typically present in the following approximate percentages:

Cellulose	40–50%
Hemicelluloses	20–30%
Lignin	25–30%
Ash	0.1–0.5%
Extractives	1–5%

Of the major constituents, cellulose is the most easily described and is in many respects the most important. Wood cellulose is chemically defined as $(C_6H_{10}O_5)_n$, the basic monomer of which is called glucose anhydride. As shown in Figure 5, glucose anhydride units are alternately linked in pairs to form bimers (cellobiose), which in turn are repetitively end linked to form the long-chain linear polymer cellulose. The average degree of polymerization (DP) of cellulose is in the range of 10,000. The hemicelluloses found in wood are polysaccharides of moderate size (DP averaging 150–200 or greater) of the types that are invariably associated with cellulose and lignin in plant-cell walls. Predominant types include xylan (the principal hemicellulose in hardwoods), glucomannan, and galactoglucomannan (the major hemicellulose of softwoods). Many other forms of

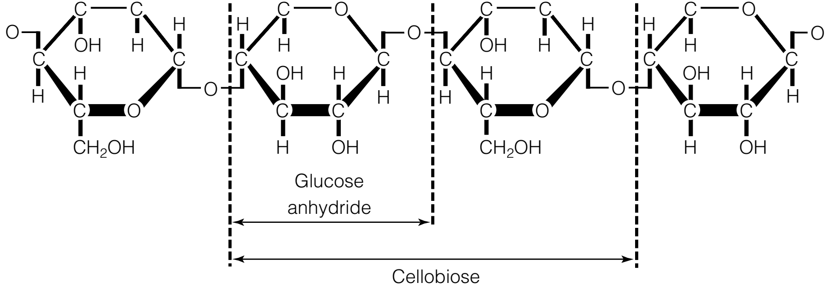


Figure 5
Representative portion of a molecule of cellulose, the major chemical constituent of wood.

hemicellulose are also present. Lignin has complex three-dimensional polymeric structure comprising various phenylpropane units. Lignin apparently infiltrates and encrusts the cell-wall structure after the polysaccharides are in place. Although lignin contributes to the compressive strength of wood, cellulose provides the major contribution to tensile strength.

Cellulose, hemicelluloses, and lignin are essentially permanent products synthesized by the developing wood cells soon after division in the cambium. Extractives are principally associated with heartwood formation and are located as much outside the cell wall as within. These extraneous materials are called extractives because they can be extracted from wood with the appropriate solvent with little change to the basic wood structure. Extractives are typically low-molecular-weight compounds that, among the various species of wood, fall within classifications such as tannins, terpenes, polyphenols, lignins, resin acids, fats, waxes, and carbohydrates. In addition to influencing the appearance of the wood, mainly as color, extractives may contribute to other properties of the wood, such as significant decay resistance in some species.

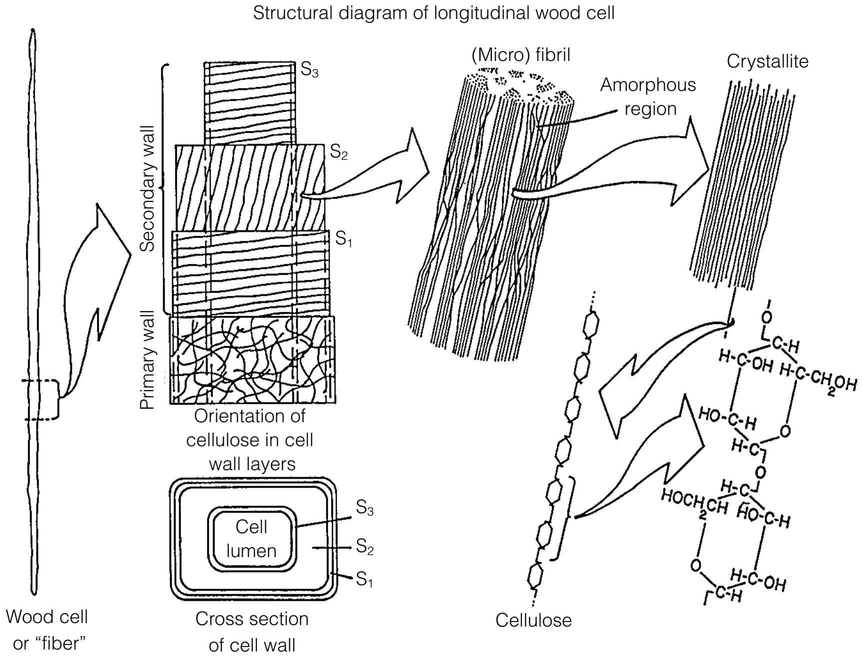
Cellulose within the cell wall

The nature and orientation of cellulose determine the architecture of the cells. Insight into the configuration of the cellulose within cell walls provides the important key to understanding and anticipating many of the properties and resulting behavior of wood.

Figure 6 presents a conceptual model representing a typical longitudinal wood cell, such as a hardwood fiber or a softwood tracheid. The cell wall has layered structure. The outer layer, the primary wall, was the functional cell wall during cell division in the cambium and during subsequent enlargement or elongation of the developing daughter cell. Immediately after enlargement the secondary wall formed within, giving permanence to the cell's dimensions and shape. The primary wall is very thin and lacks any apparent structural orientation; in contrast, the secondary wall occupies the dominant portion of the cell wall and has three layers, designated as S_1, S_2, and S_3, each with orientation revealed by striations visible under the electron microscope. The direction of these striations, as diagrammed in Figure 6, indicates the general orientation of aligned cellulose. The apparent groupings, as suggested by ridges seen in micrographs, are referred to as *fibrils* (subgroupings are sometimes termed *microfibrils*).

Within the thinner S_1 and S_3 layers, the fibril orientation is nearly perpendicular to the cell axis, whereas fibrils within the dominant S_2 layer are oriented more nearly parallel with the cell axis. Experimental evidence provides a theoretical explanation for the arrangement of cellulose within fibrils. In random areas, called crystallites, cellulose molecules (or, more likely, portions of cellulose molecules) are aligned into a compact crystalline arrangement. Adjacent areas in which cellulose is nonparallel are called amorphous regions. The hemicelluloses and lignin are also dispersed between crystallites and through the amorphous regions. Within the fibrils, water molecules cannot penetrate or disarrange the crystallites. Water molecules can, however, be absorbed by hydrogen bonding, in one or more layers, to the exposed surfaces of crystallites and components of amorphous regions—namely, at the sites of available hydroxyl groups. Such polar groups of the polysaccharide fractions on exposed wall surfaces

Figure 6
Diagrammatic model of a longitudinal wood cell, showing the orientation of fibrils within layers of the cell wall and the arrangement of cellulose within fibrils.



provide the principal active sites for bonding of adhesives and finishes and for other chemical reactions with wood. Because the average length of cellulose molecules is far greater than the apparent length of the crystallites, it is concluded that an individual cellulose molecule may extend through more than one crystalline region, being incorporated in crystal arrangement at various points along its total length. Therefore, within the fibrillar network, the random endwise connection of crystallites would appear to offer linear strength to the fibril. Since crystallites would be more readily displaced laterally from one another due to the intrusion or loss of water molecules (or other chemicals capable of entering the fibrils), dimensional response would occur perpendicular to the fibril direction.

In summary, knowledge of the linear organization of cellulose within the fibrils, the dominance of the S_2 layer, and the near-axial orientation of fibrils within the S_2 layer provides a foundation for understanding the greater strength and dimensional stability of the cell in its longitudinal, as compared to transverse, direction. It follows that wood itself—as the composite of its countless cells—has oriented properties.

Wood-Moisture Relationships

Virtually every property or response of wood, from its strength to its decay susceptibility, is related to its moisture condition—but probably no property is of greater concern than its dimensional behavior in response to moisture. We recognize that such problems as warping and checking of panels and flaking of paint are among the most challenging conservation issues. If there is to be a hope of preventing or correcting such problems, the fundamental relationships involving wood, moisture, and the atmosphere must be recognized.

Before exploring interrelated details, we can easily summarize underlying principles. First, the wood in trees is wet, containing large amounts of moisture in the form of sap, which is mostly water. It is appropriate to think of wood at this stage as being fully swollen. Second, when wood is taken from trees and dried to a condition appropriate for common uses, it loses most (but not all) of its moisture. Third, the loss of moisture affects many properties: for example, it increases strength but decreases dimension (i.e., causes shrinkage). Fourth, after initial drying to an equilibrium with its environment, wood remains hygroscopic and will continue to adsorb or desorb moisture, and consequently change dimension or other properties, in response to changes in relative humidity (RH). Fifth, wood can remain dimensionally responsive to humidity-related moisture changes indefinitely.

Moisture content

The amount of moisture in wood is usually expressed quantitatively as moisture content (MC). The MC of wood is defined as the ratio of the weight of water in a given piece of wood to the weight of the wood when it is completely dry. The water-free weight of wood is also referred to as its oven-dry weight, determined by drying a specimen at 100–105 °C until it ceases to lose weight (loss in weight is taken as moisture loss). MC is expressed as a percentage and is calculated as follows:

$$MC = \frac{W_i - W_{od}}{W_{od}} \times 100$$

where: MC = moisture content, in percent; W_i = original weight; and W_{od} = oven-dry weight.

Forms of water in wood

Water exists in wood in two forms: bound and free. Water adsorbed and held within the cell walls by hydrogen bonding is called *bound water*. Any available moisture will be adsorbed by the cell walls until they reach saturation. Water in wood in excess of cell-wall saturation exists as liquid water in the cell cavities; it is called *free water*. The hypothetical moisture condition of wood wherein the cell walls are completely saturated with bound water but the cell cavities are devoid of free water is called the fiber saturation point (FSP). The FSP is usually expressed as a numerical value of moisture content. For common species of wood, the FSP is approximately 28–30% moisture content.

The sap contained in living trees is primarily water, with small amounts of dissolved minerals and nutrients. In living trees, the moisture content of the wood is always above the FSP, but it can vary from as low as 35–40% in some woods to 200–300% in others. When trees are harvested and the timber is seasoned for use, all the free water and some of the bound water is dried from the wood. As drying progresses, the FSP has special significance to wood properties. For example, loss of free water has no effect on strength or dimension of wood. In any portion of the wood tissue, bound water is not lost until all free water is dissipated. Only when wood is dried below the FSP does the loss of bound water effect an increase of strength and a reduction of dimension.

Hygroscopicity

Cell-wall substance is hygroscopic—that is, wood has the capability of exchanging bound water in the cell walls by adsorption or desorption directly with the atmosphere. When wood is seasoned, the amount of bound water that is lost, as well as the amount that remains in the wood, is determined by the RH of the atmosphere in which the drying is com-

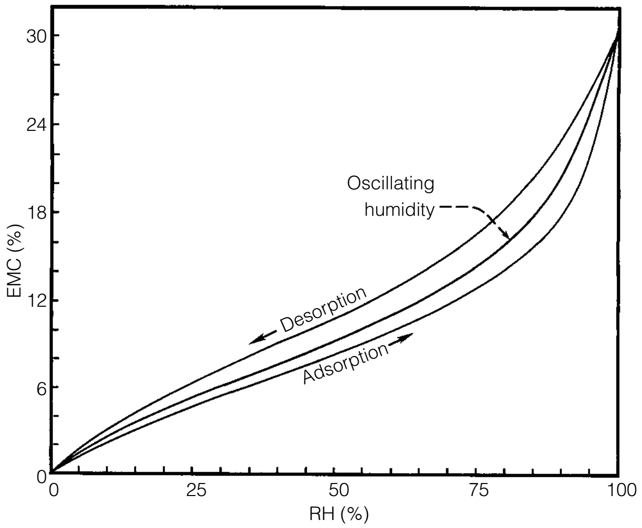


Figure 7
Relationship between environmental RH and EMC for wood, with white spruce as an example. The hysteresis effect is indicated by the different curves for desorption and adsorption in thin specimens under carefully controlled conditions. In the natural environment, with its fluctuating humidity, wood of lumber thickness attains average MCs as indicated by the oscillating humidity curve.

pleted. After initial drying, wood remains hygroscopic. It responds to changes in atmospheric humidity and loses bound water as RH decreases, or regains bound water as RH increases.

The moisture condition established when the amount of bound water is in balance with the ambient RH is called the equilibrium moisture content (EMC). The extremely important relationship between EMC and RH is shown in Figure 7. The figure contains average data for white spruce, a typical species, shown as having an FSP of about 30% of the moisture content. The FSP varies somewhat among different species: for woods having a high extractive content, such as rosewood or mahogany, the FSP can be as low as 22–24%; for those low in extractives, such as beech or birch, the FSP might be as high as 32–34%. Temperature also has an effect on EMC. The curves shown are for 21 °C, but at intermediate humidities the EMC would be about one percentage point lower for every 14–16 °C elevation in temperature. The EMC curves always converge at 0% RH and 0% EMC, so variation due to extractives and temperature will therefore be most pronounced toward the FSP end of the relationship.

Under conditions in which the RH is closely controlled, as in laboratory treatments or experiments, the curve for wood that is losing moisture (a desorption curve) is significantly higher than the curve for wood that is gaining moisture (an adsorption curve), as illustrated in Figure 7. This effect is called hysteresis. During the conditioning of wooden objects under precisely controlled laboratory conditions, the hysteresis effect may be apparent. Under normal room or outdoor conditions of fluctuating RH, an averaging effect results, usually referred to as the oscillating curve.

Moisture-Related Dimensional Change

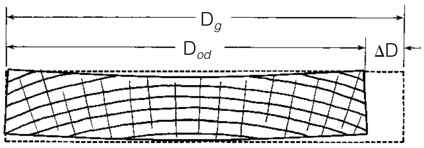
As with most physical solids, wood responds dimensionally to thermal changes—expanding when heated, contracting when cooled. However, the coefficient of thermal linear expansion for wood is relatively quite small—about a third of the value for steel. For most uses of wood, such minute dimensional change is insignificant to an object's performance and is usually ignored; therefore, thermal expansion or contraction of wood will not be covered here. Moisture-related shrinkage and swelling of wood, however, is of critical importance and is the major contributor to warping and cracking of painting panels. The following discussion addresses the dimensional change in wood due to changes in MC below the FSP.

Shrinkage percentage

The traditional approach to expressing the relative dimensional instability of wood is to measure the total amount of linear shrinkage that takes place in a given direction from its green[1] condition to its oven-dry condition, expressed as a percentage of the green dimension. Linear dimensional change in wood is usually measured separately in the three principal directions: longitudinal (S_l), radial (S_r), and tangential (S_t). Quantitatively, the total shrinkage percentage is calculated as follows:

$$S = \frac{D_g - D_{od}}{D_g} \times 100$$

where: S = shrinkage, in percent, for a given direction (S_l, S_r, or S_t); D_g = green dimension; and D_{od} = oven-dry dimension.



$$S_t = \frac{\Delta D}{D_g} \times 100$$

Figure 8

Determination of the total shrinkage percentage for wood. Tangential shrinkage percentage (S_t) is calculated as the change in dimension after oven drying ($\Delta D = D_g - D_{od}$), divided by the original green dimension (D_g).

Figure 8 illustrates the application of the formula in the determination of tangential shrinkage (S_t) based on green and oven-dry measurements of a tangentially sawn strip of wood.

Total longitudinal shrinkage of wood (S_l) is normally in the range of 0.1–0.2%. In practical situations involving typical moisture-content changes over a moderate range, only a portion of this small quantity would be affected, and the resulting dimensional change becomes insignificant. It is therefore reasonable to assume that wood is stable along its grain direction, and for most purposes longitudinal shrinkage and swelling can be ignored—in fact, longitudinal shrinkage data are not commonly available. It should be cautioned, however, that abnormal wood tissue, such as juvenile wood, reaction wood, or cross-grain pieces may exhibit longitudinal shrinkage of up to ten to twenty times that of normal. In addition, it should be expected that abnormal wood will occur unevenly in severity and in distribution, and the resulting uneven longitudinal shrinkage will cause warp.

Radial shrinkage is quite significant, and tangential shrinkage is always greater than radial. Tangential shrinkage varies among species over the range of about 4–12%, with an overall average of about 8%. Average radial shrinkage values range from about 2% to 8%, averaging slightly over 4%. Values of average tangential and radial shrinkage are given for woods commonly found in painting panels in Table 1.

Over the range of bound-water loss, shrinkage of wood is roughly proportional to MC change, as shown by solid-line curves in Figure 9. Careful measurement of changing dimension as wood is slowly dried will show nonproportional behavior, especially at MCs near the FSP, because of the moisture gradient inherent in drying. However, in theory, the effect of MC on shrinkage is essentially proportional, and the relationship is assumed to be linear (see dashed-line curves, Fig. 9).

Estimating dimensional change

Based upon published percentages of shrinkage for individual species and upon the assumption that shrinkage bears a linear relationship to moisture content, the anticipated dimensional change in a given piece of wood can be estimated. Because shrinkage percentages are averages and exact

Table 1 Total (green to oven-dry) tangential and radial shrinkage percentages for selected woods typically found in painting panels. For most woods, the values listed are estimates averaged from various sources for the more common species of the genus. (For more extensive listing of shrinkage values for individual species, consult the following references: Chudnoff 1984; Princes Risborough Laboratory 1972, 1977; U.S. Department of Agriculture 1987.)

		Shrinkage (%)	
Common name	Scientific name	Tangential	Radial
SOFTWOODS			
Spruce	*Picea* spp.	7.4	3.6
Fir	*Abies* spp.	7.6	3.8
Pine, Scots	*Pinus sylvestris*	7.7	4.0
Larch	*Larix* spp.	7.8	3.3
HARDWOODS			
Mahogany	*Swietenia* spp.	5.1	3.2
Walnut, European	*Juglans regia*	6.4	4.3
Chestnut	*Castanea* spp.	6.8	4.0
Willow	*Salix* spp.	7.2	4.2
Alder	*Alnus* spp.	7.3	4.4
Cherry	*Prunus* spp.	7.8	4.2
Ash	*Fraxinus* spp.	8.3	5.2
Poplar	*Populus* spp.	8.5	3.4
Maple	*Acer* spp.	8.8	4.2
Elm	*Ulmus* spp.	9.1	5.2
Lime	*Tilia* spp.	9.5	6.8
Oak, white	*Quercus* spp.	10.2	5.2
Beech	*Fagus* spp.	11.8	5.8

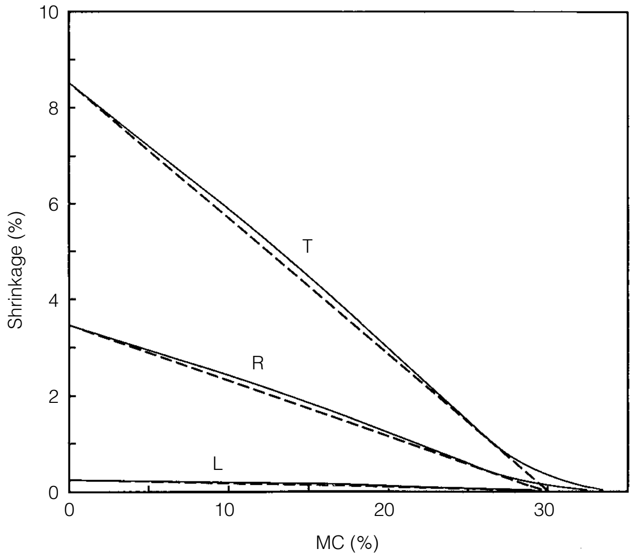


Figure 9
Relationship between MC and shrinkage in the tangential (*T*), radial (*R*), and longitudinal (*L*) directions. Plotted data represent a typical wood such as poplar. Experimental results of carefully dried wood are shown as solid curves. As indicated by dashed lines, a linear relationship is assumed for calculations of approximate shrinkage behavior.

moisture content cannot be predicted, expected dimensional change cannot be calculated with precision. The theoretical dimensional change for a given piece of wood can be calculated using the following formula:

$$\Delta D = \frac{D_i(MC_i - MC_f)}{\frac{FSP}{S} - FSP + MC_i}$$

where: ΔD = dimensional change, in linear units; D_i = initial dimension, in linear units; MC_i = initial moisture content, in percent; MC_f = final moisture content, in percent; FSP = fiber saturation point, in percent (if not known for species, use 30%); and S = published value for shrinkage, in percent (S_l, S_r, or S_t).

In calculating dimensional change for pieces of wood with intermediate or variable growth-ring placement, a modified shrinkage percentage would have to be estimated by rough interpolation between the radial and tangential values. It should be noted that because shrinkage takes place only below the FSP, neither MC_i nor MC_f can be greater than the FSP. Positive values of dimensional change indicate shrinkage; negative values indicate swelling.

As an example, suppose a painting panel is assembled by the edge-gluing of flat-sawn boards that have been identified as poplar (*Populus* spp.); the finished panel measures 76 cm in width. The panel is placed in a building where records have shown a seasonal variation from a high of 60% RH in the summer to a low of 25% during the winter heating season. What dimensional changes in width can be expected?

From the oscillating curve of Figure 7, one can assume EMC extremes of a high moisture content (MC_i) of 10.9%, a low moisture content (MC_f) of 5.4%, and an FSP of 30%. From Table 1, S_t for poplar is given as 8.5%.

The estimated change in the width of the panel from its summer to its winter condition is calculated as

$$\Delta D = \frac{76\text{ cm }(10.9\% - 5.4\%)}{\frac{30\%}{8.5\%} - 30\% + 10.9\%}$$

$$= \frac{76\text{ cm }(0.109 - 0.054)}{\frac{0.30}{0.085} - 0.30 + 0.109}$$

$$= \frac{76\text{ cm }(0.055)}{3.338} = 1.25\text{ cm}$$

The panel would be assumed capable of shrinking by approximately 1.25 cm. It is important to realize that this calculation would predict the behavior of normal wood free to move, whereas a painting panel may be subject to restraint by its frame and cradling or mounting hardware and by the applied layers of gesso and paint.

Careful evaluation of the formula presented above leads to some important general conclusions. It is apparent that the overall dimensional change, ΔD, is directly influenced by the magnitude of each of the three factors D_i, S, and ΔMC (i.e., $MC_i - MC_f$), which should be considered separately. In the conservation of painting panels, the overall dimensions and species of the panel wood are already determined; the change in MC is the variable within our control.

It must be emphasized that the calculations given above are of theoretical value in understanding potential dimensional change; however, in practical terms they are approximations at best. The formula for predicting dimensional change in unrestrained wood has been found to be no more accurate than ±25%. It would therefore seem fitting to consider a simple graphic method of approximating dimensional change.

Combining the oscillating curve of Figure 7 with the principle of Figure 9, a composite working graph might be devised as shown in Figure 10. For the right-hand portion of the graph, the appropriate shrinkage percentage (S_t, S_r, or interpolated estimate) is taken from published data according to the panel at hand. Users of the graph may translate estimates of changes in RH into percentage dimensional change by following initial and final RH values up and over to corresponding EMC values, then over and down to corresponding S values.

The graphic solution can be applied to the problem discussed above. In the example already proposed, charted graphically as example 1 in Figure 10, a change in RH from 60% to 25% would result in a shrinkage of approximately 1.6% for tangentially cut poplar.

As a numerical check for the calculation of dimensional change in the poplar panel discussed above, if D_i were considered simply as one unit of dimension, the value of ΔD would have been calculated as:

$$\frac{1\,(0.109 - 0.054)}{\dfrac{0.30}{0.085} - 0.30 + 0.109} = \frac{0.055}{3.338} = 0.0165, \text{ or } 1.65\%$$

Therefore, (76 cm)(1.65%) = (76 cm)(0.0165) = 1.25 cm.

The graphic relationship among RH, MC, and shrinkage draws attention to the point that RH is the important controlling parameter, and dimensional change is the eventual consequence. Too often RH is not given the serious attention it deserves. Although weight of wood is usually not of direct concern, it can be important indirectly if we remember that it reflects the MC. A painting probably loses or gains weight primarily as a response to changes in the MC of its wooden panel. Therefore, the simple monitoring of the weight of a painting, especially when it is being

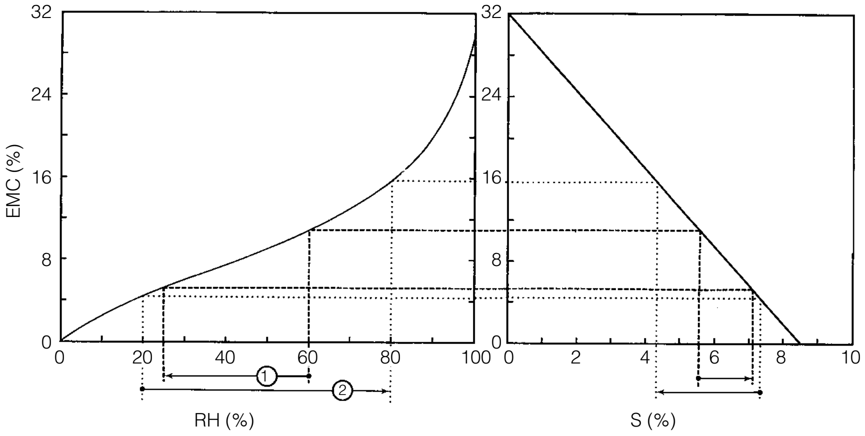


Figure 10

Relationship between RH and EMC, and between EMC and shrinkage *(S)*, shown for tangentially cut poplar (S_t = 8.5%). As shown by dashed and dotted lines, the two examples discussed in the text illustrate the effect of RH change on potential shrinkage and swelling (negative shrinkage).

transported or relocated to a new environment, would be an excellent way to detect changing conditions that might eventually result in dimensional-change problems. The relative amount and rate of weight gain or loss could signal developing problems.

With time, the dimensional response of wood may lessen slightly, in part because hygroscopicity of the wood may decrease or because of the mechanical effects of repeated shrinkage/swelling cycles or stress setting of the wood. Nevertheless, experiments with wood taken from artifacts thousands of years old have shown that the wood has retained its hygroscopicity and its capacity to dimensionally respond to changes in MC. The assumption should therefore prevail that wooden objects, regardless of age, can move dimensionally when subjected to variable RH conditions.

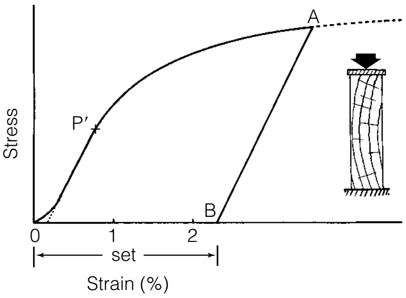


Figure 11
Diagrammatic stress/strain relationship plotted for a wooden element compressed tangentially beyond its proportional/elastic limit (P′) to point A. When unloaded, strain recovers only to point B, resulting in permanent set.

Restrained swelling and compression shrinkage

An important consequence of dimensional behavior occurs when wood is mechanically restrained from the swelling that would normally be associated with increased MC. If transverse swelling of wood is restrained, the effect is that of compression by the amount of the restraint. The consequence is therefore best understood in terms of the mechanical properties of wood in compression perpendicular to the grain.

As shown in Figure 11, the elastic limit of transverse compressibility of wood is typically between 0.5 and 1%, and compression beyond this elastic limit results in permanent strain, or *set*. The importance of the low elastic limit is evident when it is compared quantitatively to typical values of free swelling of wood subject to common variation in RH, with its resultant MC change. For example, consider a panel prepared from tangentially cut boards of poplar with an average tangential shrinkage percentage (from Table 1) of 8.5%. Suppose further that the panel had been prepared from wood in equilibrium at 20% RH and mounted into a frame that would confine it from swelling along its edges, and that the panel were later subjected to a humidity of 80% until EMC was reached. As shown in Figure 10, example 2, a change from 20% to 80% RH would be expected to produce a swelling (negative shrinkage) of approximately 3% in an unrestrained panel. However, given our restrained panel with an elastic limit of less than 1%, at least two-thirds of its restrained swelling is manifested as compression set. If the panel is eventually reconditioned to the original 20% humidity, it would recover only its elastic strain and would shrink to a dimension some 2% or more smaller than its dimension at the original MC. This loss of dimension from cyclic moisture variation under restraint is called *compression shrinkage*. This mechanism is a very common cause—and perhaps the one most often incorrectly diagnosed—of dimensional problems in wooden objects. Too often any loss of dimension of a wooden component is interpreted simply as "shrinkage," with the assumption that MC must be lower than it was originally.

Cracks and open gaps in painting panels that are attributed to simple drying and shrinkage may in fact be traceable to compression shrinkage induced by restrained swelling. The elastic limit in tension perpendicular to the grain is of similar magnitude to that in compression—0.5–1%.

However, the compression set accumulated by excessive restrained swelling cannot simply be reversed by continuing the restraint of the panel during the drying/shrinkage phase of the cycle, because the amount of tensile strain is limited to about 1.5%, whereupon failure occurs. Therefore, if a panel has its edges fastened in place rather than being simply confined, it may show no ill effects during the humid/swelling phase of the cycle but may crack open when redried to its original moisture condition.

The classic experiment shown diagrammatically in Figure 12 demonstrates the typical extreme consequences of restrained swelling and compression shrinkage in panels.

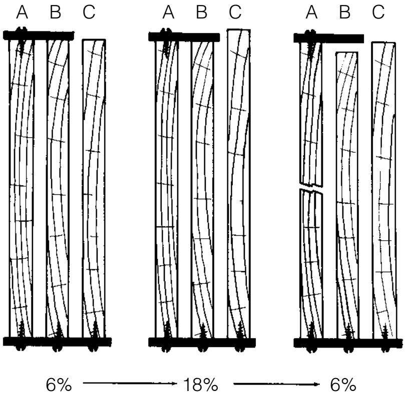


Figure 12
Classic experimental demonstration of the effects of restrained swelling and compression shrinkage on elements of wood representing panels. At an initially low MC, three matched specimens are machined to equal tangential dimension. Element A is restrained and fastened to rigid restraining surfaces at both edges, element B is restrained but fastened only at one edge, and element C is unrestrained and fastened only at one edge. All elements are slowly conditioned to a high MC and then brought back to the original low MC. The restrained specimens, A and B, show typical consequences of compression shrinkage.

Warp

Although dimensional change alone may be a serious consequence of moisture variation, even minor amounts of uneven shrinkage or swelling can cause warp, defined broadly as the distortion of a piece from its desired or intended shape. Various forms of warp include *cup* (deviation from flatness across the width of a board), *bow* (deviation from lengthwise flatness of a board), *crook* (departure from end-to-end straightness along the edge of a board), and *twist* (in which four corners of a flat face do not lie in the same plane).

In painting panels, cupping is perhaps the most commonly encountered form of warp and can result from a variety of causes, singly or in combination. Uneven moisture change in opposite faces of a panel may cause a slight, and usually temporary, cupping concave to the drier face, which may disappear as moisture equalizes through the thickness of the panel. Growth-ring placement within a board is an important factor in the determination of cupping potential. Quarter-sawn (radially cut) boards tend to remain flat as MC changes. Flat-sawn (tangentially cut) boards, however, routinely cup, or attempt to cup, as they season (Fig. 13). Cupping results from the different components of tangential and radial grain orientation across opposite faces of the boards. Panels fashioned from flat-sawn boards will tend to cup additionally as MC varies. If

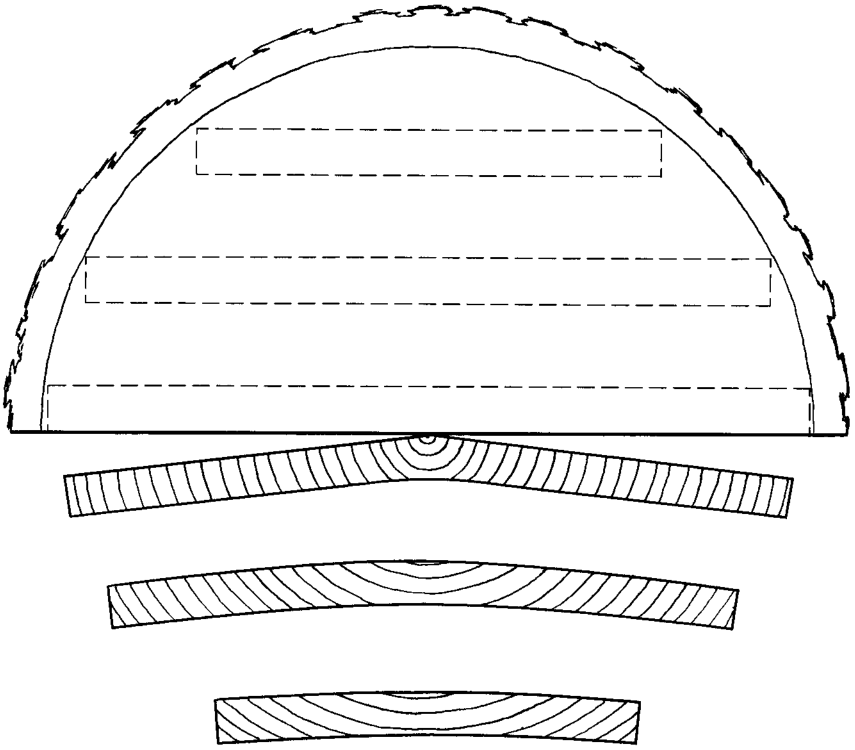


Figure 13
Warp in flat-sawn (tangentially cut) boards during seasoning. The severity and distribution of cupping is related to the location in the log and the resulting curvature of growth rings, as well as to the tangential/radial ratio of shrinkage percentages. Note that flat-sawn boards located closest to the pith have the most severe cup, concentrated near the center. Panels that are held flat may crack if the normal cupping is prevented.

flat-sawn boards or panels are held flat and restrained from attempted cupping, cracking may result along the grain into the concave face.

A less obvious source of cupping in painting panels is compression shrinkage. The causal mechanism is typified by a panel painted only on the face side, its unpainted back therefore exposed to much more rapid moisture sorption. In the case of such a panel originally coated with gesso and painted when the wood was at a fairly low MC, subsequent exposure to high humidity causes the wood at the back surface to adsorb moisture and go into compression set. If the panel were mounted by fastening at its edges, the expected cupping concave to the painted surface would be largely restrained. Upon restoration of a normally low humidity condition, the rear of the panel now manifests its compression shrinkage and shortens; the panel then cups concave to the unpainted surface. This mechanism is commonly the real source of cupping that has been attributed to tangential/radial shrinkage and "drying out." Uneven compression shrinkage can overshadow the effects of tangential/radial shrinkage and can also produce cupping in radially cut panels that would otherwise remain flat under simple moisture cycling.

Note

1 The term *green* as applied to wood suggests the moisture condition in the living tree or in freshly cut timber. However, because many important properties, such as dimension and strength, are unchanged by loss of free water, green wood is taken as any condition of MC above the FSP.

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Identification of Wood in Painting Panels

R. Bruce Hoadley

Through many centuries wooden panels were a standard surface for artistic painting. In such works of art, the rendering itself typically receives intensive examination, whereas the panel supporting the painting is sometimes evaluated simply as wood, with little concern as to its species or characteristics. In modern conservation and curatorial investigation, however, there is increasing appreciation for the potential importance of identifying the wood of panels. Considering the natural range of an identified species of wood may have important implications as to the geographic origin of a painting. It may become evident that individual artists or regions preferred certain woods or that some woods were chosen over others because of properties such as dimensional stability or ease of seasoning without defects. Finally, proper identification of wood is fundamental to conservation treatment when repair or replacement is involved or when it is important to anticipate the properties or behavior of a panel.

Simply stated, the process of wood identification usually involves the visual recognition of anatomical features of the wood that singly or in combination are known to be unique to a particular species or group of species. Physical properties such as color, odor, specific gravity, relative hardness, or reaction to chemical reagents may sometimes be helpful, but the most important diagnostic features of the wood relate to its cellular structure. Therefore, an understanding of the basics of wood anatomy is fundamental to wood identification.

Visual features—that is, those apparent without magnification—are the obvious starting point of the identification process and may provide at least an indication of the wood's identity. In most cases, however, portions of the wood must be examined under magnification. An initial classification of an unknown wood is routinely made by observing features evident with a hand lens on end-grain surfaces prepared with a razor blade or sharp knife. Final determination, or verification of tentative visual or hand-lens results, is best made on the basis of minute detail observed in razor-cut thin sections of wood tissue examined with a microscope.

For the more common woods, the necessary features for identification are soon learned and memorized, and thorough examination of macroscopic and microscopic detail gives an immediate identification. Otherwise, the compiled characteristics can be compared directly with samples of known wood, with photographs or descriptive reference material, or with information in computer databases. Expertise in wood identification therefore requires at least a general familiarity with the anatomical characteristics and nomenclature of wood as well as the availability of suitable reference material for the woods being considered.

It is beyond the scope of this article to present a complete treatise on wood anatomy and the identification of all woods that might be encountered in painted panels. Instead, an attempt will be made to provide a primer of the basics of wood anatomy along with routine approaches and techniques for wood identification. In addition, a summary of pertinent features and the identification process is presented for a selection of woods—a sampler of sorts—most commonly found in painting panels.

Woods and Their Names

Taxonomy, the science of classifying living things, provides a systematic approach to the study of wood tissue, as closely related trees can be expected to have similarities of anatomical features. Wood identification therefore finds its foundation in taxonomy, and narrowing the identity of an unknown piece of wood to its tree species follows closely the taxonomic network. In taxonomic classification, woody plants of tree sizes in temperate regions of the world are found principally in either of two classes, the gymnosperms, which include the conifers, or *softwoods,* and the angiosperms, wherein the *hardwoods* occur. In turn, classes are divided into orders, families, genera (singular: genus), and, finally, species (Table 1).

Each species is designated by a scientific name, a Latinized, italicized binomial term comprising its genus name followed by its species name, or *epithet*. For example, the species we know by the common name of black poplar has the scientific name of *Populus nigra—Populus* indicating the generic name for all poplars and *nigra* the epithet for the black poplar species. Botanical names are universally accepted among scientific disciplines, and their usage is therefore preferred in order to prevent the confusion that may result when a species has a number of common or local names in a particular language. For example, Norway spruce, *Picea abies,* is also known in English as European spruce or simply as whitewood.

The ultimate objective in wood identification is to determine the species of tree from which a particular piece of wood originated, and it is therefore always proper and desirable to use the species name to designate a piece of its wood. Unfortunately, the woods of species within a genus (such as, for example, the poplars) are commonly so similar that they lack distinguishing features and cannot be separated. In this situation the scientific name of the genus is given, followed by the designation "sp." (plural: spp.), printed in roman (not italic) script. As an example, a painting panel might, in fact, be black poplar but can perhaps only be identified as poplar; it is therefore designated *Populus* sp.

Wood Anatomy: The Basis for Identification

Wood identification is based primarily on anatomical structure and should proceed with the awareness that wood is a composite mass of countless numbers of cells. These cells were produced by cell division of the cambium, the layer of reproductive tissue beneath the tree's bark, and the cyclic variations of this growth process are recognizable in most woods as growth rings. Each wood cell has an outer wall that surrounds an internal cavity. In the living tree, a cell cavity may contain a living protoplast, or at least some liquid sap, whereas in the wood found in painted panels, the now-dried cells are defined by their walls, their central cavities apparently empty in most cases.

Wood cells are typically elongated, varying from short barrel shapes (sometimes large enough in diameter to be individually visible) to extremely long fibers that are too small in diameter to be seen individually without considerable magnification. Most of the cells—usually more than 90%—are elongated in the direction of the tree stem or branch. These cells are termed *longitudinal* cells in relation to the stem axis. The remainder of the cells are *ray* cells, elongated horizontally in the tree and therefore perpendicular to the longitudinal cells. Ray cells, arranged to form flat, ribbonlike groups, radiate outward from the central pith of the stem. If just the longitudinal cells could be removed without disturbance to the ray cells, the rays in a tree stem would appear somewhat like bristles in a giant bottlebrush.

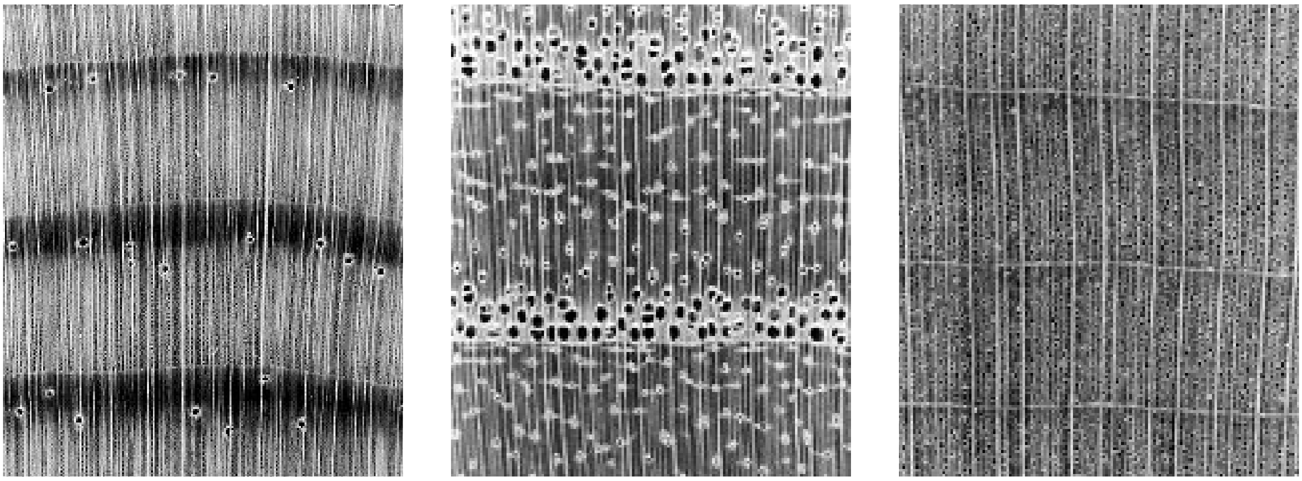
Wood Identification Techniques

There is no single technique or method of wood identification best for every situation or for every species. Surely the investigator begins the process by taking advantage of any obvious features that may immediately suggest an answer. Only a few woods, however, such as oak (*Quercus* spp.) and beech (*Fagus* spp.), have unique visual features that enable fairly reliable identification. Among the other woods, visual features such as distinctive heartwood color, as in walnut (*Juglans* spp.) and cherry (*Prunus* spp.), or physical properties, such as the greater density and hardness of maple (*Acer* spp.) as compared to the lightness and softness of poplar (*Populus* spp.), are occasionally helpful. However, colors may fade or deepen with age, density may be difficult to assess in panels that are framed or cradled, and overall visual features may be obscured by gesso or by the painting itself. Further examination requires magnification.

Hand-lens examination

Beyond the casual observation of visual features discussed above, the next step is to determine the orientation of the grain in the wood and then to find a location where the wood can be cut across the grain, such that the longitudinal cells will be exposed in cross section. In painting panels these locations will be along two opposite edges of the panel. An area of approximately 5–10 mm square will usually reveal important information. The final surfacing cuts should be made with a razor-sharp instrument to ensure that the wood tissue is cleanly severed so that cellular detail will be visible. A surface so exposed is called a transverse surface, a cross-sectional surface, or an end-grain surface.

The width and placement of the growth layers (growth rings) are usually immediately apparent. In a few species of hardwoods, such as oak, chestnut (*Castanea* spp.), ash (*Fraxinus* spp.), and mahogany (*Swietenia* spp.), the cells forming vessels (called *pores* when exposed on transverse surface) are large enough to be individually visible without magnification. And, with magnification, even the smallest pores can also be seen. A 10× magnifier, referred to simply as a hand lens, is most commonly used. Hand-lens examination also serves to separate the hardwoods, in which all longitudinal cells appear uniformly small. Figure 1a–c demonstrates the appearance of typical softwood and hardwood end-grain surfaces as seen under low-power magnification.



a

b

c

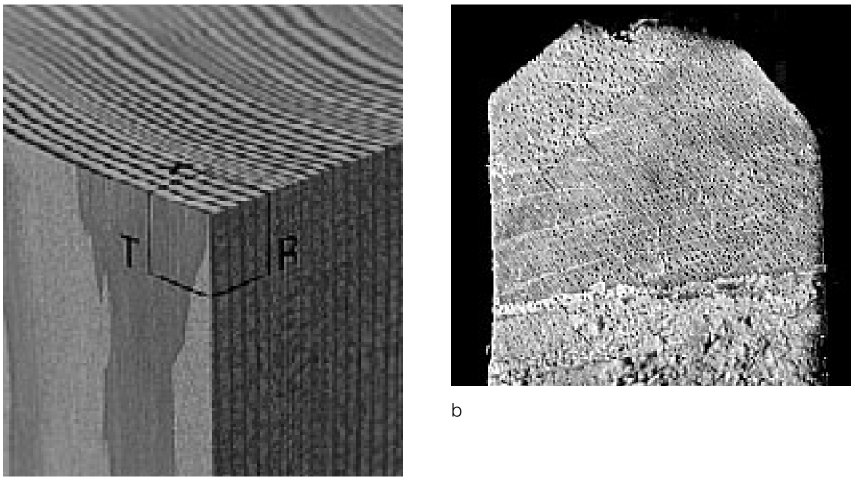
Figure 1a–c
Woods can be initially classified into general types by examination of transverse surfaces with a 10× hand lens. Examples shown are (a) a softwood, pine (*Pinus sylvestris*), (b) a ring-porous hardwood, ash (*Fraxinus* sp.), and (c) a diffuse-porous hardwood, maple (*Acer* sp.).

Microscopic examination

For microscopic examination of wood, thin sections taken from the transverse surface are sometimes useful, but the most valuable information is usually found in radial and tangential sections. Examination of a cleanly cut end-grain surface with a hand lens reveals the orientation of radial and tangential directions in the area of the wood sample under scrutiny, and accessible surfaces can be split or shaved down along the radial and tangential planes in the grain direction. The tangential plane is formed parallel to the growth rings, the radial plane perpendicular to the growth rings. Figure 2 illustrates the principal planes of wood structure and the preparation of small areas of radial and tangential surfaces with respect to the transverse surface.

During work on painting panels, it is often possible to cut sections directly from a corner edge of the panel. In other cases it may be more expedient to use material removed in conservation work or simply to remove a small piece for identification. A piece 3 × 3 × 10 mm will typically be sufficient.

From the surface of any of the principal planes of the panel or wood sample, a tiny slice of tissue is carefully sliced off with a razor blade.



a

b

Figure 2a, b
Block of softwood (*Pseudotsuga menziesii,* Douglas-fir) (a) machined to expose principal planes: X = transverse (cross-sectional or end-grain); R = radial; T = tangential. A small portion of the end-grain edge of this panel of poplar (*Populus* sp.) was surfaced with a razor blade (b). On this exposed transverse surface, the anatomical orientation is revealed on the basis of the growth ring and ray placement. The upper right corner was beveled parallel to the rays to produce a radial plane. The upper left corner was then beveled parallel to the growth ring to produce a tangential plane. From the surfaces of any of these principal planes, thin tissue sections can be taken for microscopic examination.

The section is placed on a glass microscope slide and covered with a thin cover glass; enough water is added with an eyedropper to surround the tissue section without excessively flooding the area under the cover glass. When placed on the stage of a standard compound light microscope, the translucent section is illuminated with transmitted light, and the cellular detail can be examined at magnifications up to 500× (Fig. 3).

Slicing of the section is most critical to success. Initial surfacing cuts might be made with a sharp knife, a replaceable scalpel blade, or an industrial-type razor blade, but sectioning of tissue is best done with a double-edged or equivalent-quality razor blade, although these blades may be too fragile for higher-density woods, especially on transverse surfaces. It helps to moisten surfaces with water prior to sectioning. For small pieces removed from the panel, sectioning will be much easier if the sample is boiled or soaked in hot water for a few minutes. Sections should be removed with a smooth, sliding, slicing action, rather than by pushing or forcing the cutting edge directly forward.

Sections should be sliced as thinly as possible, ideally not more than one or two cell diameters thick. Skimming off several tiny, thin bits (1–2 mm across) will usually yield better results than attempting to take a larger single section, which will be mostly too thick to show detail. With hand sectioning, the sections will not be uniformly thin, but if they are well cut, they will have appropriately thin areas near their edges where detail will be visible.

Survey of Panel Woods

Table 1 lists woods common to painting panels. This selection will probably account for the species found in well over 95% of painting panels. Species within most genera cannot be separated on the basis of wood tissue alone. Nevertheless, in cases in which different species are found in distinctly different geographic localities, the known origin of a painting may suggest a probable identification. This section presents key diagnostic features of the woods listed in Table 1 and provides the reader with a foundation for identifying them in painting panels. It is highly recommended, however, that the reader examine known samples of woods and consult

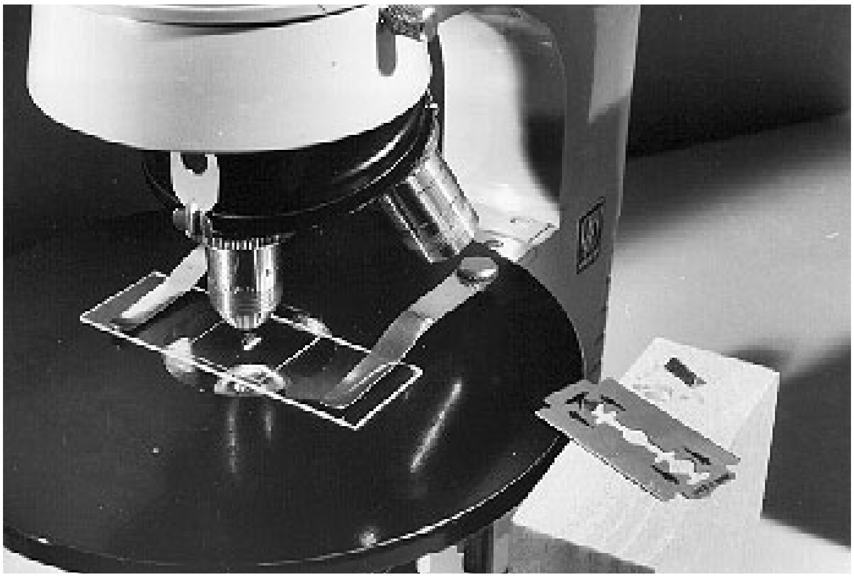


Figure 3
The small specimen of wood near the razor blade is sufficient for identification. A clean cut of a transverse surface reveals the orientation of the rays and growth rings, enabling accurate radial and tangential surfaces to be prepared. From any of the three principal surfaces, a tiny, thin section can be removed with a razor blade and mounted on a slide with a drop of water for microscopic examination, as shown.

Table 1 Selected woods found in painted panels. Generic designations of woods are followed by examples of the more common European species.

Common name	Scientific name	Figures
SOFTWOODS (CONIFERS)		
Fir	*Abies* spp.	7, 9c
silver fir	*A. alba*	
Larch	*Larix* spp.	6, 10b
European larch	*L. decidua*	
Spruce	*Picea* spp.	5, 8, 9b, 10a
Norway spruce, European spruce, whitewood	*P. abies*	
Pine	*Pinus* spp.	
Scots pine	*P. sylvestris*	1a, 4, 9a
HARDWOODS		
Maple	*Acer* spp.	1c, 19, 26b, 27d, 27e
field maple	*A. campestre*	
Norway maple	*A. platanoides*	
sycamore, great maple	*A. pseudoplatanus*	
Alder	*Alnus* spp.	18, 24a, 25b
common alder, black alder, European alder	*A. glutinosa*	
gray alder	*A. incana*	
Chestnut	*Castanea* spp.	12
sweet chestnut, European chestnut	*C. sativa*	
Beech	*Fagus* spp.	17, 27f
European beech	*F. sylvatica*	
Ash	*Fraxinus* spp.	1b, 13
European ash	*F. excelsior*	
Walnut	*Juglans* spp.	15
European walnut	*J. regia*	
Poplar	*Populus* spp.	2b, 23, 24b, 25a, 27a, 28a
white poplar	*P. alba*	
black Italian poplar	*P. canadensis* var. *serotina*	
black poplar	*P. nigra*	
European aspen	*P. tremula*	
Cherry	*Prunus* spp.	20, 26c
European cherry, wild cherry	*P. avium*	
Pear	*Pyrus* spp.	21
common pear	*P. communis*	
Oak	*Quercus* spp.	11
Turkey oak	*Q. cerris*	
holly oak, holm oak	*Q. ilex*	
sessile oak, durmast oak	*Q. petraea*	
pubescent oak, white oak	*Q. pubescens*	
common oak, pedunculate oak	*Q. robur*	
Willow	*Salix* spp.	28b
white willow	*S. alba*	
Mahogany	*Swietenia* spp.	16, 25c, 27b, 29
Central American mahogany	*S. macrophylla*	
Lime	*Tilia* spp.	22, 26a, 27c
small-leaved lime	*T. cordata*	
large-leaved lime	*T. platyphyllos*	
European lime	*T. vulgaris*	
Elm	*Ulmus* spp.	14
smooth-leaved elm	*U. carpinifolia*	
wych elm	*U. glabra*	
Dutch elm	*U. hollandica* var. *hollandica*	
English elm	*U. procera*	

references of wood anatomy to see how variable or how consistent different specimens of a species can be.

The equipment necessary for a wood identification procedure includes a sharp knife or other woodworking tool for exposing fresh wood surfaces or for removing small specimens, razor blades (single- and double-edged types) for final surfacing and sectioning, a 10× hand lens, a transmission light microscope (capable of magnification up to 400–500×), glass slides, cover glasses, and an eyedropper. It is preferable that the investigator have reference samples of the species under consideration so that he or she can compare key features to those seen in the reference samples rather than relying on the written material and photographs alone.

As an initial step, a transverse surface of the unknown wood should be examined with a hand lens to determine whether the wood is a hardwood or a softwood. If there is any difficulty in establishing this distinction, a transverse section quickly examined under the microscope will show the radial rows of tracheids that characterize softwoods or the varied cell types with larger pores characteristic of all hardwoods.

Softwoods

With the hand lens alone, identification of the conifers is tentative at best, but it is usually worthwhile to evaluate any noteworthy macroscopic features. Coniferous wood tissue consists mainly of small and indistinct tracheids, and in transverse view the overall cellular appearance is confusingly similar among all conifers, as shown among the examples presented in Figures 4–7. Within a growth ring the contrast between earlywood and latewood may be characteristic. For example, in Scots pine (*Pinus sylvestris*) and larch (*Larix* spp.) there is a rather abrupt transition from the lighter mass of earlywood tracheids to the darker, denser latewood; in spruce (*Picea* spp.) and fir (*Abies* spp.) there is less contrast between earlywood and latewood, and the transition from earlywood to latewood is more gradual than abrupt.

One important feature seen under the hand lens is resin canals, which are tubular passageways formed by a cylindrical sheath of cells called epithelial cells. During the sapwood stage, the epithelial cells are living and exude resin into the resin canals. The resin canals, being three to five times the diameter of the surrounding tracheids, are visible on transverse surfaces under a hand lens. Among the conifers covered in this article, resin canals are present in pine (*Pinus* spp.), spruce, and larch (Figs. 4–6). Fir, however, does not contain resin canals (Fig. 7).

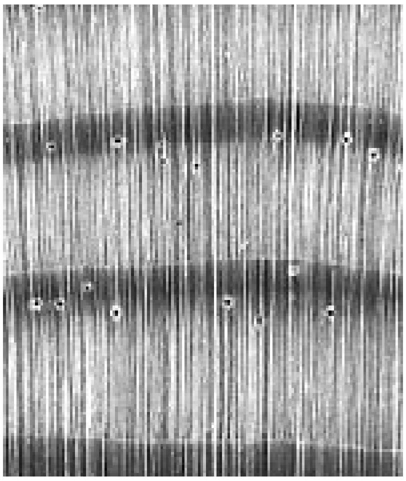
In pines the resin canals are large, solitary, and usually conspicuous, relatively numerous, and uniformly distributed in virtually every growth ring. In spruce and larch the resin canals are smaller and less numerous, and they tend to occur unevenly. They are apparently absent in some growth rings but may occur in tangential groups of two or more.

For coniferous woods, observations such as those discussed above will suggest possible answers, but minute features evident through microscopic examination of tangential and radial thin sections provide the most reliable basis for identification.

Routinely useful microscopic features include the height and width of the rays (as determined by cell count) viewed tangentially; in radial view, diagnostic features include the types of ray cells present, the shape and number of cell-wall pits (voids in the cell walls connecting to

Figure 4, right
Pine (*Pinus sylvestris*), transverse surface.

Figure 5, far right
Spruce (*Picea* sp.), transverse surface.



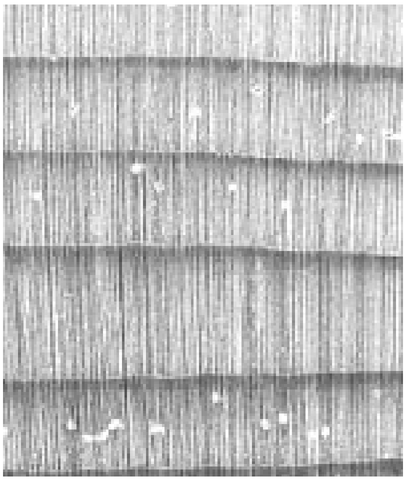
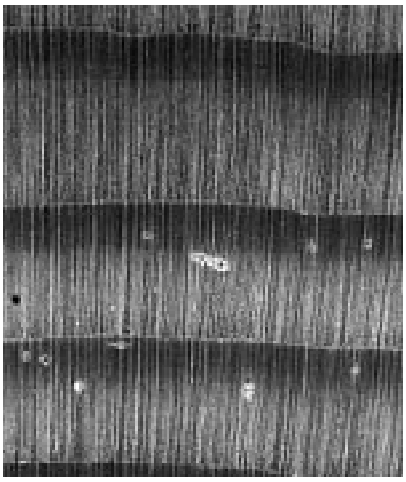
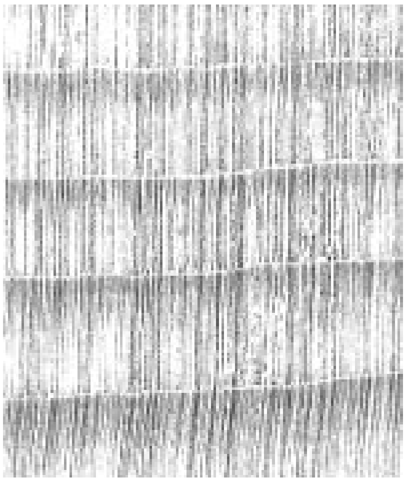


Figure 6, right
Larch (*Larix* sp.), transverse surface.

Figure 7, far right
Fir (*Abies* sp.), transverse surface.





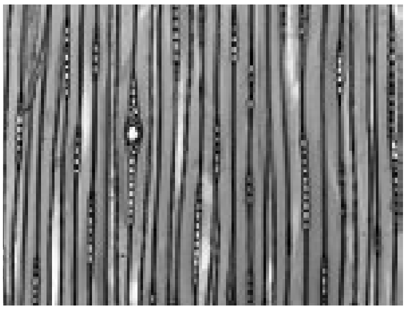


Figure 8
Tangential section of spruce (*Picea* sp.) showing several uniseriate rays and one fusiform ray with a centrally located transverse resin canal.

matching pits in adjacent cells), the smoothness of the cell walls, and the presence and color of the cell contents. Conifers that contain vertical resin canals, evident on transverse surfaces, also contain horizontal resin canals located within special rays called *fusiform* rays (Fig. 8). Therefore, the presence of resin canals can be confirmed by locating fusiform rays on tangential sections examined microscopically. Scots pine and fir are separated from one another and from spruce and larch by microscopic examination of radial sections (Figs. 9a–c). On such sections, groups of smaller (horizontal) ray cells will be evident crossing perpendicular to the larger (vertical) longitudinal tracheids. Of special significance are the *cross fields*—the rectangular areas formed where individual ray cells contact individual longitudinal tracheids. The pits occurring on these cross fields are classified in terms of size and shape. Scots pine, the principal pine of Europe and Asia, is distinct in having dentate ray tracheids (tracheids with jagged or toothed walls) and large cross-field pits (called windowlike pits) in the ray parenchyma cells (Fig. 9a). European larch (*Larix decidua*) and Norway spruce (*Picea abies*) have more or less smooth-walled ray tracheids and small multiple cross-field pits (called piceoid pits, each typically a rounded pit with a diagonal slash, similar in appearance to the Greek letter *phi*) in the ray parenchyma cells (Fig. 9b). Larch and spruce are separated by examination (in radial sections) of the first-formed longitudinal tracheids

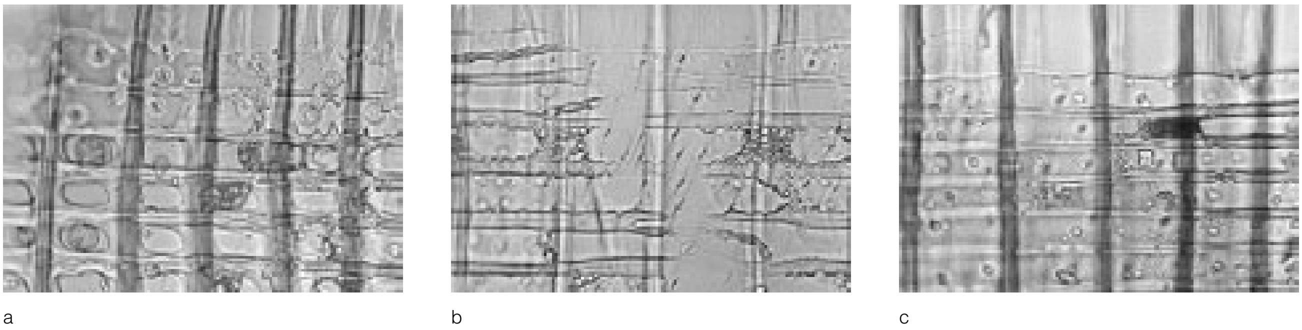


Figure 9a–c
Radial sections of (a) Scots pine *(Pinus sylvestris)* showing a portion of a ray: the upper two rows of ray cells are dentate ray tracheids, and the lower four rows of cells are ray parenchyma with large windowlike cross-field pitting; (b) spruce (*Picea* sp.) showing a portion of a ray; the upper and lower two rows of ray cells are ray tracheids, and the central two rows of cells are ray parenchyma with piceoid cross-field pitting; and (c) fir (*Abies* sp.) showing a portion of a ray: all ray cells are ray parenchyma with taxodioid cross-field pitting, and crystals are present in the third row (counted from the top) of ray parenchyma.

in the earlywood. In spruce, along a given earlywood tracheid, the large bordered pit pairs on the radial walls occur singly and only occasionally are paired; in larch, tracheids with many consecutive paired pits will be commonly found (Fig. 10a, b).

If no resin canals are seen on the transverse surface with the hand lens or if a tangential section reveals no fusiform rays, the wood may be fir. Microscopic examination of a radial section will reveal that ray tracheids are absent and that all rows of ray cells are of the same type of cells—ray parenchyma. The cross fields have multiple small pits called taxodioid pits, rounded pits with narrow borders appearing like the capital letter O (Fig. 9c).

It is always possible that the unknown wood under consideration is none of those described here. If the features of an unknown do not seem to agree closely with any of the woods described here, it is necessary to consult the literature to pursue a more thorough investigation. For example, there are numerous other pines that also have large resin canals but non-dentate ray tracheids or other types of cross-field pitting. For example, other softwoods that have been found in painting panels include the true cedars, *Cedrus* spp. (cedars may also contain resin canals and fusiform rays), and Mediterranean cypress, *Cupressus sempervirens* (containing longitudinal parenchyma, vertically oriented cells occurring among the longitudinal tracheids; they have dark contents, conspicuous when observed microscopically).

Hardwoods

The hardwoods can be roughly classified by examination of transverse surfaces with a hand lens and evaluation of the size and arrangement of pores. If the wood has relatively large pores grouped into the first-formed portion of the growth ring, forming a conspicuous zone, the wood is

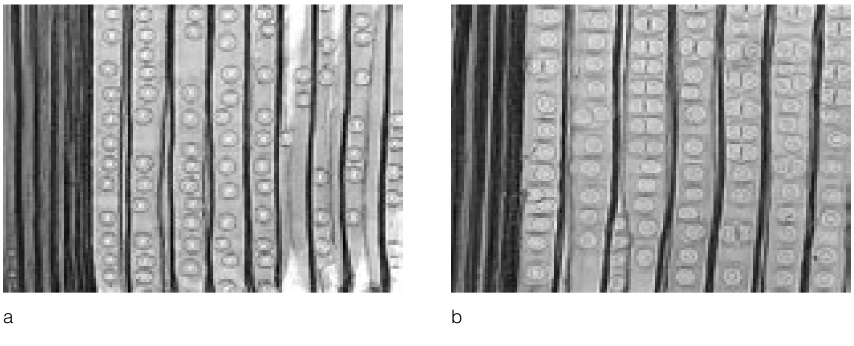
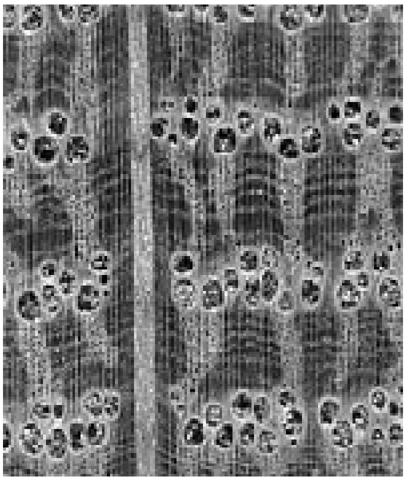


Figure 10a, b
Radial sections showing bordered pits on radial walls of longitudinal tracheids in earlywood. In (a) spruce (*Picea* spp.), bordered pits are usually unpaired; and in (b) larch (*Larix* spp.), bordered pits are commonly paired.

Figure 11, right
Oak (*Quercus* sp.), transverse surface.

Figure 12, far right
Chestnut (*Castanea* sp.), transverse surface.



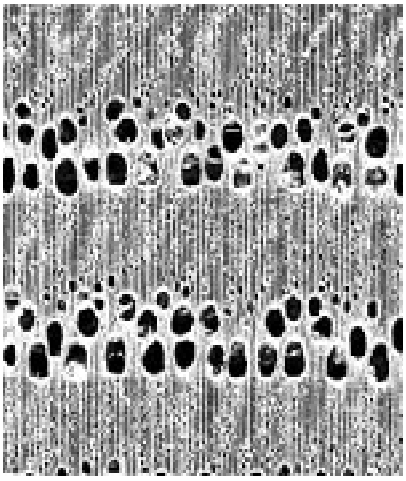
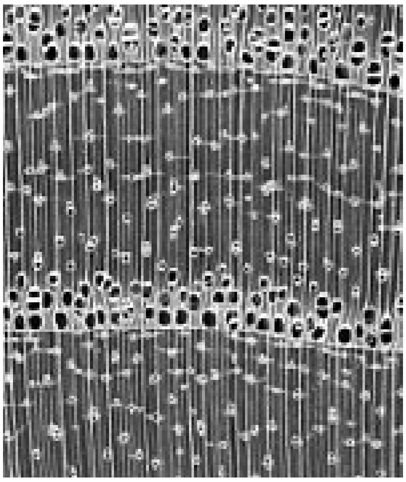
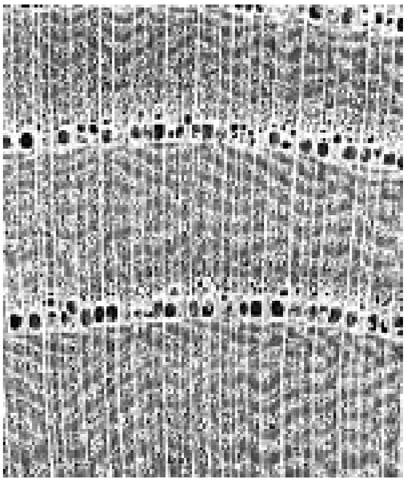


Figure 13, right
Ash (*Fraxinus* sp.), transverse surface.

Figure 14, far right
Elm (*Ulmus* sp.), transverse surface.





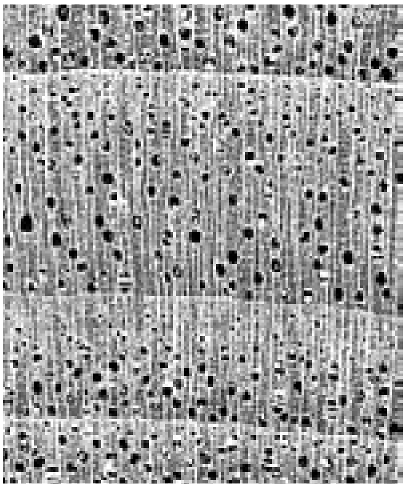


Figure 15
Walnut (*Juglans* sp.), transverse surface.

classified as ring porous. Examples of woods in this category include oak, chestnut, ash, and elm (*Ulmus* spp.) (Figs. 11–14). If large earlywood pores do not form a distinct zone, the wood may be considered semi-ring-porous, as walnut (Fig. 15). If the pores appear uniform in size and are evenly distributed throughout the growth ring, the wood is diffuse porous (Figs. 16–23). Tropical hardwoods are commonly diffuse porous, and in many tropical species the pores are relatively large, as in mahogany. Most diffuse-porous hardwoods of the temperate regions are fine textured: that is, the pores are relatively small in diameter, as in maple or poplar.

Although pores are visible with a hand lens, all other cells are too small in diameter to be seen individually on transverse surfaces. Groups or masses of cells may, however, be recognized. Masses of denser, thick-walled fiber cells usually form a darker background mass against which groups of thinner-walled parenchyma cells produce lighter-colored zones, lines, or patterns that may be characteristic of a species. For example, the tangential lines of parenchyma are distinctly visible in mahogany (Fig. 16). Perpendicular to the growth rings, the rather straight lines of the rays are also apparent. Rays range in size among hardwoods, from large and conspicuous in oak and beech to fine and barely perceptible with a hand lens on transverse surfaces in poplar and pear.

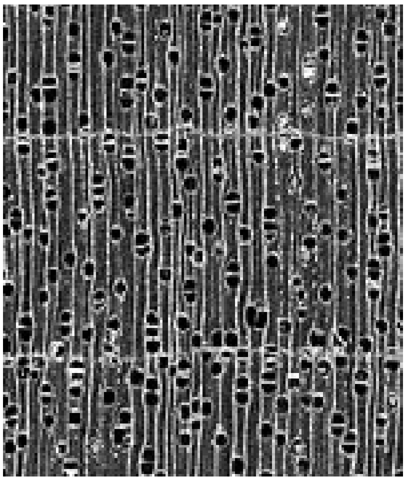


Figure 16
Mahogany (*Swietenia* sp.), transverse surface.

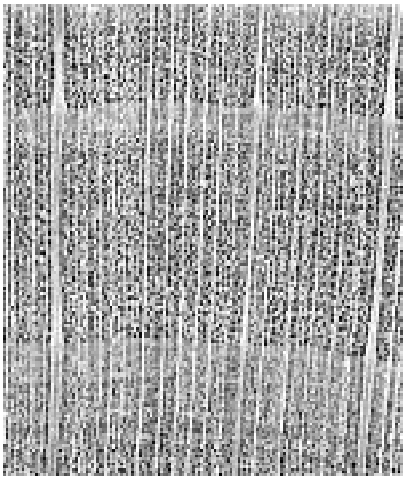


Figure 17
Beech (*Fagus* sp.), transverse surface.

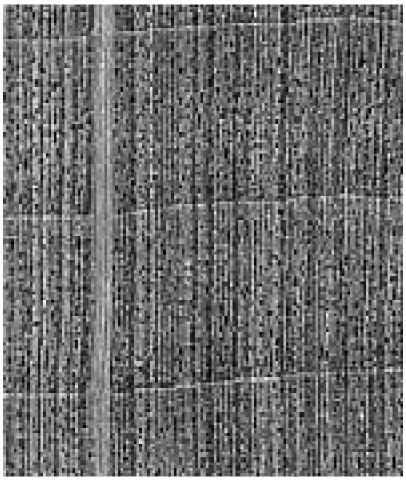


Figure 18
Alder (*Alnus* sp.), transverse surface.

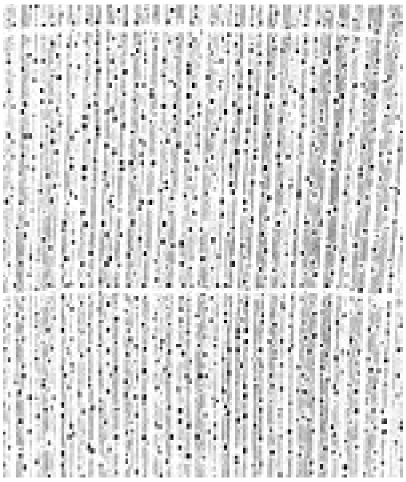


Figure 19
Maple (*Acer* sp.), transverse surface.

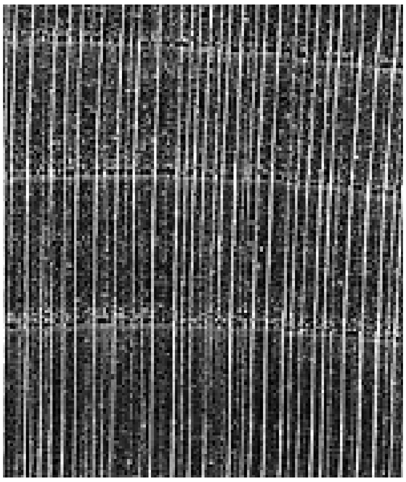


Figure 20
Cherry (*Prunus* sp.), transverse surface.

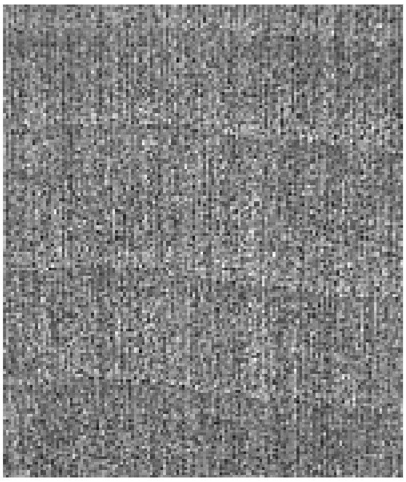


Figure 21
Pear (*Pyrus* sp.), transverse surface.

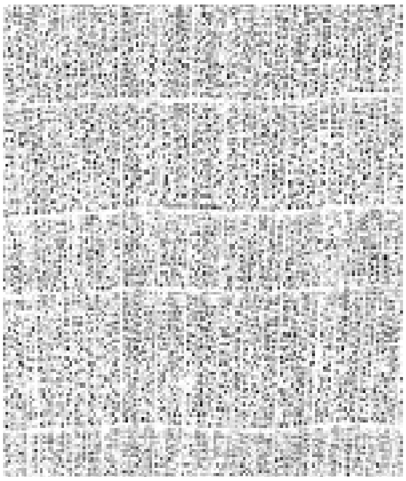


Figure 22
Lime (*Tilia* sp.), transverse surface.

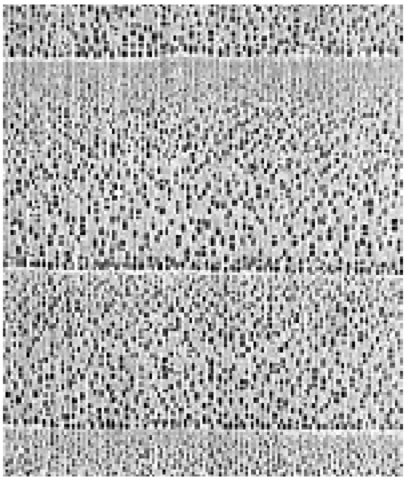


Figure 23
Poplar (*Populus* sp.), transverse surface.

In summary, with nothing more than a hand lens, some hardwoods can be identified at least to the level of their genus by the size and distribution of the pores, the size and distinctiveness of rays, and characteristic patterns of parenchyma cells.

Among the hardwoods, especially the diffuse-porous hardwoods, microscopic analysis also provides the best means of confirming many genera and sometimes provides a means of separating species within a genus. Useful features include ray seriation (the width of a ray determined by a count of the number of cells across the ray as viewed in tangential section), the type of perforations (openings of the end walls of vessel cells), the type of intervessel pitting (distinctive patterns of multiple pits in cell walls connecting vessels laterally), and the presence or absence of spiral thickenings on the walls of vessels.

Ring-porous and semi-ring-porous hardwoods

When end-grain surfaces are examined with a hand lens, four of the hardwoods presented here stand out as ring-porous woods by virtue of the conspicuously larger pores forming a distinct row or zone of earlywood in each growth ring, as is clearly seen in Figures 11–14. Woods with pores varying gradually in size, from larger earlywood pores to smaller latewood pores, and without clearly defined earlywood and latewood zones are classified as semi-ring-porous (synonymous with semi-diffuse-porous) woods. An example is walnut (Fig. 15). Ring-porous and semi-ring-porous woods can usually be reliably identified by careful consideration of features seen under a hand lens, although it is good practice to verify the identification by a check of appropriate microscopic features.

In *oak* (Fig. 11), the regular occurrence of very large rays is the key feature; they are visible on virtually any surface, forming conspicuous radial lines across transverse surfaces and visible as distinct lines up to several inches long along tangential surfaces. On radial cuts the rays emerge as irregular but conspicuous patches of contrasting tissue referred to as *ray fleck*. Microscopic examination of a tangential section reveals that the large conspicuous rays are up to thirty to forty cells wide and thus are *multiseriate*. Among these are the countless narrow rays that are only one cell, called *uniseriate*.

In *chestnut* (Fig. 12), as in oak, the latewood pores occur in irregular patches that wander radially across the latewood, and these latewood pores are distinguishable with a hand lens near the earlywood but diminish to invisibly small and numerous in the outer latewood. But unlike oak, chestnut lacks any large multiseriate rays, and a microscopic check of a tangential section reveals that the rays in chestnut are exclusively uniseriate, a feature unique among ring-porous timber of the temperate regions.

Ash (Fig. 13) exhibits a distinct zone of large earlywood pores. The mass of tissue surrounding the earlywood pores appears lighter than the denser fiber mass of the latewood. Pores in the first-formed latewood are solitary or in radial multiples of two or three, with each pore or multiple surrounded by a narrow band of lighter-colored parenchyma cells. In the outer latewood, pairs or short strings of pores often appear to be connected by lighter parenchyma, forming short irregular tangential lines. As a microscopic check, note that the latewood pores (vessels) are thick walled, and in European ash (*Fraximus excelsior*) the rays are commonly 3 and 4 seriate.

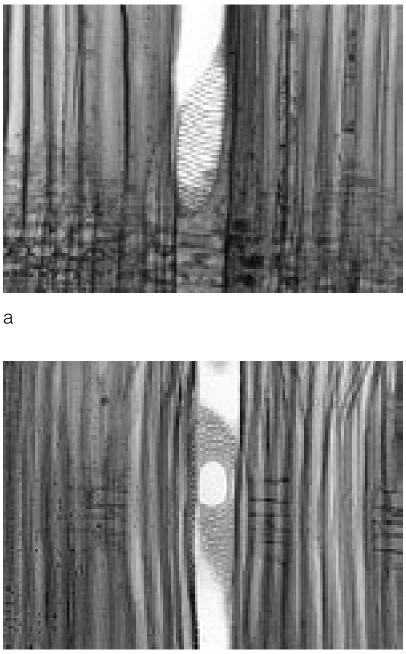
Elm (Fig. 14) has an easily recognized feature of wavy bands of pores dominating the latewood portion of the growth rings. These undulating, more or less tangential bands are up to several pores wide and give the latewood portion of growth rings a distinctive jagged appearance on tangential board surfaces. A microscopic check of tangential sections will show rays to be mostly 4–6 seriate.

Walnut (Fig. 15) is a typical semi-ring-porous wood. The larger pores are usually visible without magnification, but pore size diminishes across the growth ring, and the smallest latewood pores can be seen only with a hand lens. Pores are solitary or in radial multiples of two to four. Rays are distinct but not conspicuous when viewed on transverse surfaces with a hand lens; on tangential surfaces examined microscopically, rays of European walnut *(Juglans regia)* are mostly 2–4 (occasionally 5) seriate. The milk-chocolate color of the heartwood is also an important identification characteristic.

Diffuse-porous hardwoods

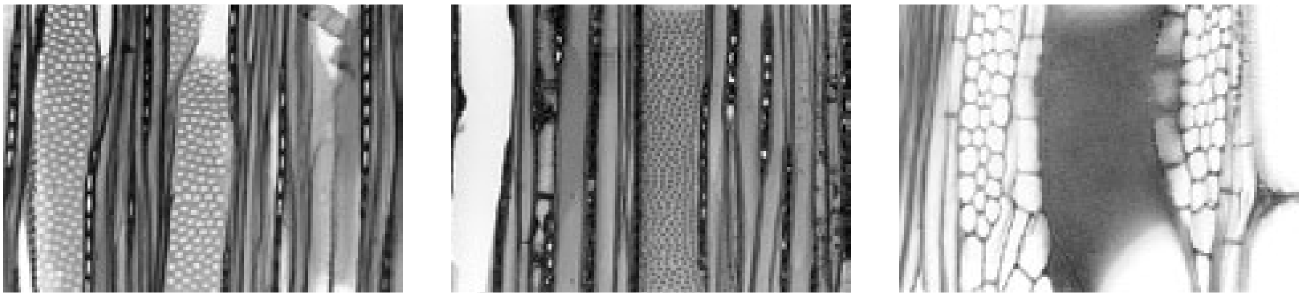
Woods in this group lack a distinct earlywood zone of larger pores when examined in transverse surface with a hand lens. The term *diffuse porous* implies that pores of more or less uniform size are distributed evenly across the growth ring. Pores may be relatively large, as in many coarse-textured tropical woods such as mahogany (Fig. 16); the largest pores of coarse-textured hardwoods are visible without magnification, and the large-diameter vessels exposed lengthwise along tangential or radial surfaces appear as distinct lines (called vessel lines). Diffuse-porous hardwoods of the temperate regions, however, are typically fine textured; the relatively small pores cannot be seen without magnification, and vessel lines are indistinct to invisible. In a few woods, such as mahogany and cherry, heartwood color may be useful. But most diffuse-porous woods are nondistinctive pale shades of light brown and, especially after centuries of aging, some darken while others lighten. Ray size is helpful in identifying some; pore size and arrangements are helpful in identifying others. A few woods have characteristic patterns of parenchyma cells. With most diffuse-porous woods, however, reliable identification requires the determination of microscopic features.

Vessel cells have several important microscopic features. The distinctive characteristic of vessel cells is that their end walls have openings where they are joined end to end. These openings, called perforations, enable the aligned vessel cells to form continuous conductive pipelines—i.e., vessels. In most species the perforations are single large openings called *simple perforations;* in other species, the vessel end walls have a series of elongated openings separated by thin bars and forming ladderlike or gratelike openings called *scalariform perforations*. A few species have both types of perforations. They are best viewed in radial sections (Fig. 24a, b). Another important microscopic feature is intervessel pitting (pits are small voids in the cell walls). Where two vessels are in contact side by side (as where a pore multiple is seen on a transverse surface), the common wall joining the two vessels is relatively wide and has numerous pits. Because pore multiples are more commonly radial, the shared tangential vessel walls with intervessel pitting are most easily found by scanning tangential sections. The appearance of these intervessel pits (size, shape, and arrangement) may be an important identification characteristic for a


a

b

Figure 24a, b
Radial sections showing examples of perforations, the openings in the end walls of adjoining vessel cells in hardwoods: (a) scalariform perforations in alder (*Alnus* sp.); and (b) a simple perforation in poplar (*Populus* sp.).



a

b

c

Figure 25a–c
Tangential sections showing examples of intervessel pitting in hardwoods: (a) large intervessel pits in poplar (*Populus* sp.); (b) medium-sized intervessel pits in alder (*Alnus* sp.); and (c) very small and numerous intervessel pits in mahogany (*Swietenia* sp.).

species (Fig. 25a–c). In some species the vessels have spiral thickenings. In longitudinal sections, they appear somewhat like coiled springs within the vessels (Fig. 26a–c).

As previously mentioned, ray seriation is a valuable microscopic feature (Fig. 27a–f). Also, pitting where ray cells contact the radial walls of vessels, called ray-vessel pitting, may have a characteristic appearance (Fig. 28a, b).

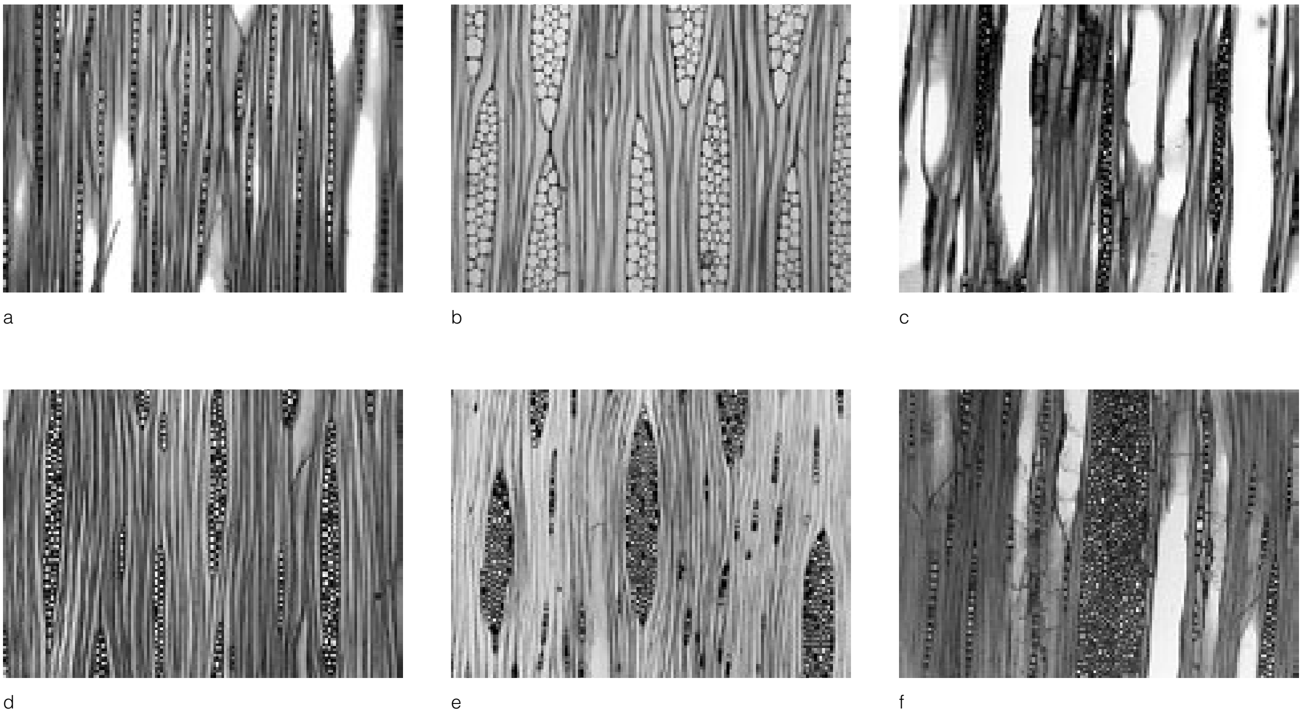
Mahogany from the tropical Americas and the West Indies found its way to Europe through the earliest trade routes. Mahogany is an extremely variable wood in both color and density and defies simple description. Heartwood color varies from medium to deep reddish brown. Some wood is straight grained, but interlocked grain is common, resulting in a ribbon or stripe figure on radially cut panels. The coarse-textured wood displays vessel lines on longitudinal surfaces. Growth rings are commonly delineated by terminal parenchyma, visible as fine, creamy light tangential lines on cross-sectional surfaces and visible among the figured patterns on longitudinal panel surfaces. Seen with a hand lens, the rays are usually conspicuous on transverse surfaces (Fig. 16). A few pores appear to contain chalk-white inclusions; others have dark contents. The rays of mahogany are often storied (occurring in a tiered arrangement as viewed on tangential surfaces), so that ripple marks are produced (Fig. 29). In tangential sections examined microscopically, the reddish or amber contents of the vessels are often conspicuous; rays are 1–6 (mostly 3–4) seriate, with relatively large-diameter cells (Fig. 27b). An important microscopic feature of mahogany is the extremely minute and numerous intervessel pitting, the individual pits measuring only 2–3 μm in diameter. This feature serves to separate mahogany from many other woods that resemble it—Spanish-cedar (*Cedrela* spp.), for example—in which the intervessel pits average 6–8 μm in diameter.

Figure 26a–c
Tangential sections showing examples of spiral thickenings in the vessel elements of hardwoods: (a) large-diameter spiral thickenings in lime (*Tilia* sp.); (b) fine, evenly spaced spiral thickenings in maple (*Acer* sp.); and (c) variable diameter and uneven spacing of spiral thickenings in cherry (*Prunus* sp.).

a

b

c



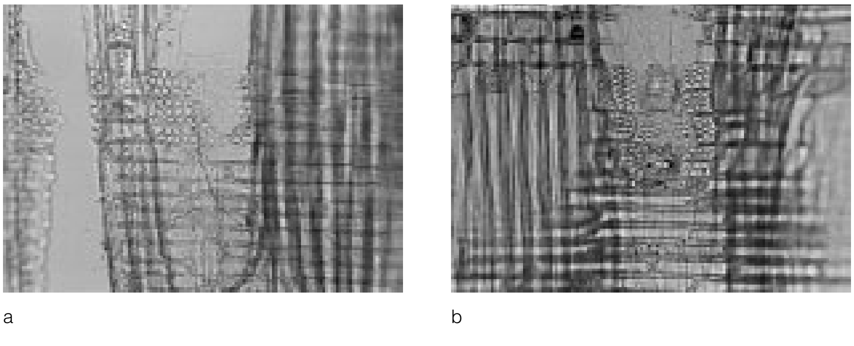
a b c d e f

Figure 27a–f
Tangential sections showing examples of ray-cell size and shape as well as ray seriation in various hardwoods: (a) uniseriate rays with flattened cells in poplar (*Populus* sp.); (b) multiseriate rays in mahogany (*Swietenia* sp.); (c) multiseriate rays with flattened to oval cells in lime (*Tilia* sp.); (d) multiseriate rays (up to 4–5 seriate) with rounded cells in soft maple (*Acer* sp.); (e) multiseriate rays (up to 8–9 seriate) with rounded cells in hard maple (*Acer* sp.); and (f) a portion of a large multiseriate ray with variable-sized cells in beech (*Fagus* sp.).

Beech can usually be identified on sight by its easily visible rays. On transverse surfaces, the largest of the rays form conspicuous light radial lines recognized quickly, especially with a hand lens (Fig. 17). On tangential panel surfaces the uniformly scattered larger rays are characteristic; on radial surfaces the rays produce a striking ray fleck of darker ray tissue against lighter background tissue. Beech is properly classified as a diffuse-porous wood, with uniformly small pores evenly distributed across most of the growth ring, although an apparent latewood zone of fewer pores terminates each growth ring. Beech may be confused with plane (*Platanus* spp.), which also has large rays. In plane, however, the rays are uniformly large and appear more crowded on tangential surfaces. Confusion is easily resolved by microscopic examination of a tangential section: in plane the rays rarely exceed 15 seriate; in beech the widest rays are up to 20–25 seriate, with many cells of very small diameter (Fig. 27f).

Alder (*Alnus* spp.) is light reddish brown, diffuse porous, and fine textured. It may be recognized on sight, however, by the occasional presence of large, conspicuous, oak-sized rays (Fig. 18). These rays are relatively few in number and may be inches apart—thus, small samples of the

Figure 28a, b
Radial sections of (a) poplar (*Populus* sp.) showing the large ray-vessel pits in the marginal rows of procumbent ray cells in contact with a vessel element; and (b) willow (*Salix* sp.) showing the large ray-vessel pits in the marginal rows of upright ray cells.



a b

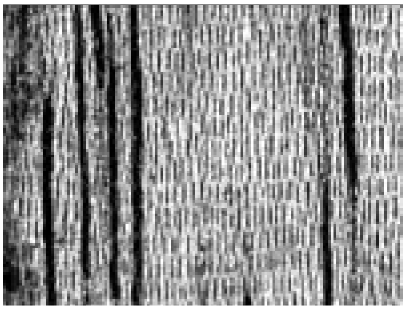


Figure 29
Tangential surface of mahogany (*Swietenia* sp.) showing storied rays resulting in ripple marks.

wood may contain no rays. In any case, the identification of alder is best confirmed by microscopic examination of longitudinal tissue sections. In tangential view, the large rays, if found, are discovered to be aggregate rays consisting of numerous closely spaced smaller rays (mostly biseriate), apparently separated by longitudinal cells. The countless other rays through most of the wood tissue are exclusively uniseriate. Intervessel pits are relatively small (4–8 μm in diameter), horizontally oval, and spaced slightly apart from one another (Fig. 25b). Radial sections show ray-vessel pitting similar to intervessel pitting, and perforation plates are scalariform with numerous fine bars (Fig. 24a).

The remaining diffuse-porous woods do not have visible features that faithfully indicate their identity. Hand-lens examination suggests possibilities at best, but final analysis should automatically proceed on the basis of microscopic features.

Maple is perhaps the paradigm of diffuse-porous structure. Hand-lens examination of end-grain surfaces shows solitary pores or short radial multiples of pores with very uniform size and distribution. Growth rings are delineated by a subtle, narrow line of slightly darker tissue, hardly sufficient to be designated as latewood. Rays appear sharply defined, appearing approximately as wide as the diameter of the larger pores (Fig. 19). On tangential panel surfaces, the rays are sometimes not evident, but on some pieces they may appear as tiny, fine, crowded but distinct lines; on radial surfaces, a conspicuous ray fleck of darker rays against the lighter background may be evident, suggesting a beech or plane ray fleck in miniature. Radial sections show simple perforations in the vessels. In tangential sections, intervessel pits appear rather large and distinct, and rounded or angular through crowding. The vessels show fine, evenly spaced spiral thickenings (Fig. 26b). In tangential sections the ray cells appear round. Rays are up to 4 to 5 seriate in the "soft maple" group (e.g., *Acer campestre* and *A. platanoides*) but up to 8 or more seriate in the "hard-maple" group (e.g., *A. pseudoplatanus*).

Cherry heartwood is distinctive in its medium cinnamon-brown to reddish brown color, which may age to a rather dark brown or reddish brown. Cherry is relatively fine textured and basically diffuse porous, although examination of a transverse surface reveals a concentration of pores, in some cases suggesting ring-porous arrangement, along the early-wood edge of the growth ring (Fig. 20). This concentration of earlywood pores contributes significantly to the figure of the wood as seen on tangential panel surfaces. Compared to maple, the pores are less evenly distributed, with multiples grouped into small clusters, the pores commonly joined tangentially as well as radially. The rays appear bright and distinct on cross-sectional surfaces and produce a characteristic light-on-dark ray fleck on radial panel surfaces of heartwood. In thin sections examined microscopically, the simple perforation plates and large, distinct intervessel pitting are similar to those of maple. An important difference, however, is in the spiral thickenings of the vessels: in cherry (Fig. 26c) the spirals appear uneven in thickness and more widely and irregularly spaced than in maple (Fig. 26b). The widest rays are up to 4 to 5 seriate with rounded cells, as in maple, but more commonly the rays show uniseriate extensions at either or both ends. There are many indistinguishably similar species of *Prunus*.

Pear (*Pyrus* spp.) has rather nondistinct visual features, the wood being very fine textured and uniformly diffuse porous (Fig. 21). In a transverse surface viewed with a hand lens, the pores are barely seen, and solitary pores appear more common than multiples. The rays are fine and inconspicuous. The wood is best identified on the basis of microscopic features: the rays are narrow, 1–3 (mostly 1 or 2) seriate. Vessels have very small (3–4 µm diameter) intervessel pits and simple (only occasionally scalariform) perforation plates. Spiral thickenings are commonly absent, although sparse spiral thickenings are occasionally present.

There are several other woods of the Rosaceae family that have anatomical features very similar to those of pear. These include apple (*Malus* spp.), hawthorn (*Crataegus* spp.), and mountain-ash (*Sorbus* spp.). Woods of this group usually cannot be separated with certainty and are summarily identified simply as fruitwood.

Lime (*Tilia* spp.) has neither characteristic visual features nor distinctive heartwood color. Hand-lens examination of transverse surfaces shows evidence of growth rings by slightly denser latewood fiber mass, the growth-ring boundary often delineated by a lighter line of latewood parenchyma (Fig. 22). Rays are fairly distinct and appear to flare (widen) as they cross the growth-ring boundary. Sections examined microscopically show vessels with simple perforations and fairly large intervessel pits. A key feature is the very thick spiral thickenings, which are conspicuous in the vessels (Fig. 26a). Tangential sections show that the rays are mostly 1–4 seriate, the ray cells appearing flattened or oval rather than rounded (Fig. 27c).

Poplar also lacks distinctive color and visual features. On cross sections viewed with a hand lens, the appearance of the pores may suggest a semi-ring-porous arrangement. Pores appear numerous, and multiples are common; the rays appear extremely narrow and are barely visible (Fig. 23). Under a microscope, tangential sections show that the rays are exclusively uniseriate (Fig. 27a). Intervessel pits are large and distinct and rounded or angular through crowding (Fig. 25a); intervessel pitting is easily found on tangential sections because of the numerous radial multiples. Vessels lack spiral thickenings, and the perforation plates are simple (Fig. 24b). Radial sections show distinctive large ray-vessel pitting in marginal rows of ray cells (Fig. 28a).

Willow appears confusingly similar to poplar and has many of the same anatomical features: diffuse-porous to semi-diffuse-porous structure with moderately fine texture, exclusively uniseriate rays, and vessels lacking spiral thickenings but with large intervessel pitting and simple perforations. The only consistent distinguishing feature is that poplar has exclusively homocellular rays, consisting entirely of radially elongated procumbent cells, whereas willow has heterocellular rays, which include both procumbent ray cells and upright ray cells (Fig. 28b). Viewed radially, upright ray cells appear more or less square or may be elongated in the longitudinal direction; they occur mostly in one or more rows along the upper and lower margins of the rays (compare Fig. 28a and Fig. 28b). The upright ray cells in willow also have distinctively large ray-vessel pits.

Summary

Among the woods commonly used in panel paintings, only a few, such as oak and beech, have visual features that suggest an immediate identification. For some, such as ash, elm, and chestnut, hand-lens examination of end-grain surfaces may suffice. For most, however, identification is best accomplished through microscopic examination of thin sections of tissue. Because the relatively short list of woods reviewed in this article covers most woods encountered in European painting panels, one can quickly learn to recognize and match the basic diagnostic anatomical features of this group.

Before any attempt is made to prepare slides for microscopic examination, the novice to wood identification should be especially apprised of two points. First, the orientation of the longitudinal direction (grain direction), as well as the placement of growth rings and rays, must be clearly understood, because sections, to be useful, must be taken along accurate transverse, radial, and tangential planes. Second, it is imperative that sections be smoothly sliced with minimum cellular damage and that they be sufficiently thin. Sections need not be large (2–3 mm is plenty), but they must be thin (ideally one to two cell diameters thick). Developing the skill of hand-slicing thin and undamaged sections with a razor blade is perhaps the greatest challenge, and mastery requires practice. Without reasonably well-made slides, attempts to identify a wood will likely be futile.

In the evaluation of the anatomical features of an unknown wood in order to match a particular species and thereby to identify it, a number of resources are recommended, including macro- and micrographs, written descriptions, and, especially, documented wood samples, from which comparison slides are prepared. Every conservation laboratory is likely to have samples of at least the more common woods. Adding samples of species that are confusing look-alikes is highly recommended.

As a final precaution, it is important to guard against the inclination to force a match of features of an unknown with those of one of the woods listed in Table 1: the conservator should always be alert to the possibility that the unknown wood is not one of the familiar or common woods.

Dendrochronological Analyses of Panel Paintings

Peter Klein

Dendrochronology is a discipline of the biological sciences that serves to determine the age of wooden objects. The method, while employed primarily for dating archaeological and architectural artifacts, is also used to solve art-historical problems (Baillie 1982; Fletcher 1978; Eckstein, Wrobel, and Aniol 1983; Eckstein, Baillie, and Egger 1984; Schweingruber 1988; Klein and Eckstein 1988). As such, it is the discipline's principal goal to give at least a terminus post quem for the creation of a painting by determining the felling date of the tree that provided the wood for the panel.

This article presents the current state of the application of dendrochronology as an aid for solving art-historical problems; also discussed are tree growth patterns and the dendrochronological methods employed.

Biological Base of Dendrochronology

A tree grows by both elongation and radial increments. The elongation takes place at the terminal portions of the shoot, branches, and roots. The radial increment is added within a particular zone of living cells between the wood and the bark. This layer, called the cambium, envelopes the woody portion of the stem, branches, and roots.

Dendrochronology focuses primarily on the annual periodicity of growth that is controlled by the climate (e.g., temperature and rainfall). In the cool and temperate climatic belt, a dormant season occurs from autumn to spring, and a growth season occurs during the summer. When the vegetative period begins in May, new cells form to conduct water from the roots to the treetop. These large cells are the earlywood cells. During the summer, around the end of June, the latewood formation starts; around the middle of September, the radial growth of the tree stops for seven months. The result is the gradual accumulation of growth during one growing season, forming an annual ring, or tree ring.

Conifers and hardwood species have different tree ring structures. In conifers—such as pine, fir, and spruce (Fig. 1a)—the wood is more or less uniformly composed of one cell type, the tracheids, and the growth ring is distinguished by differences in both cell size and cell-wall thickness between elements produced during the early and late parts of the growing season. The hardwood trees can be divided into two groups. In one, tree rings are evident because of the formation of a band of large earlywood vessels for water conduction, followed by the formation of a more compact latewood with smaller vessels and an increase in fibers, the cell

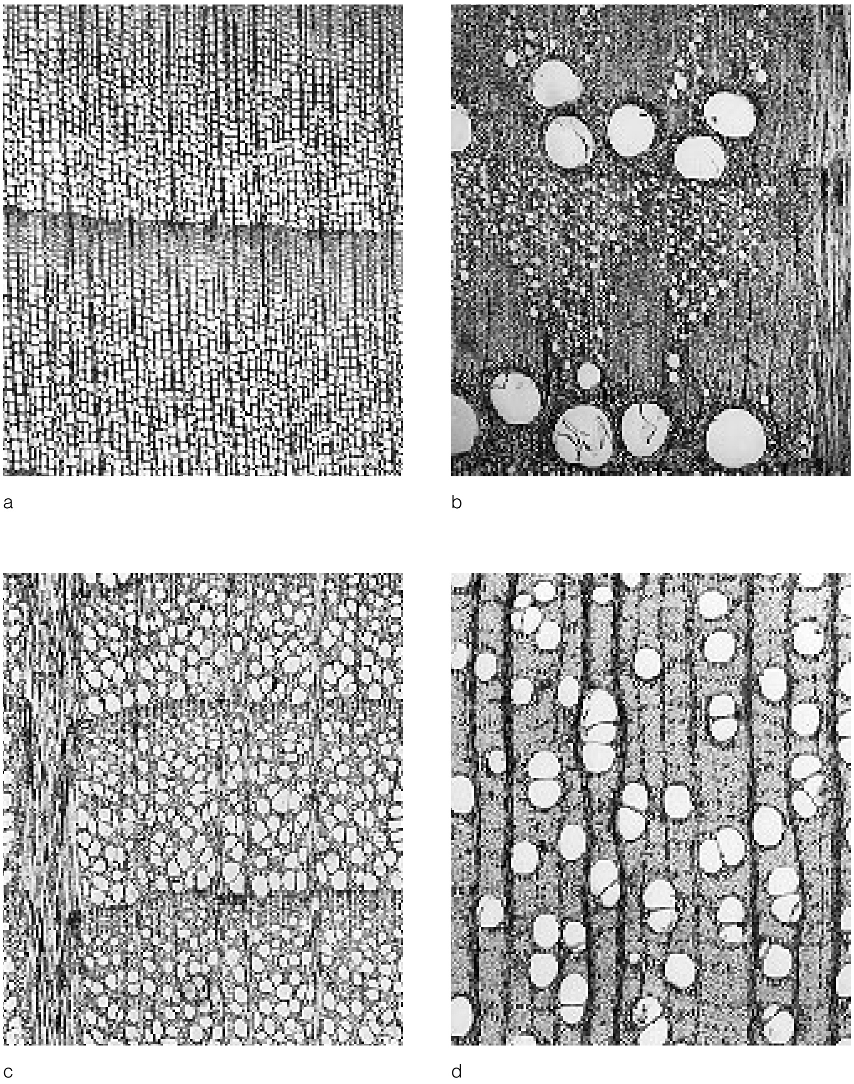


Figure 1a–d
Photomicrographs (cross sections) of (a) spruce wood (*Picea abies*); (b) oak wood (*Quercus petraea*); (c) beech wood (*Fagus sylvatica*); and (d) tropical wood (*Hopea brachyptera*). Magnification ×25.

elements that support the stem. This group—which includes oak, ash, and elm—is called *ring porous* (Fig. 1b). In the other group of hardwood trees, the growth rings are more difficult to recognize because the vessels are uniformly distributed throughout the tree ring, and the only demarcation between successive layers is either a radial flattening of the last few elements formed or an increase in fibers near the end of the growth period. This group of trees is called *diffuse porous* and includes poplar, lime, and beech (Fig. 1c). In the subtropics and tropics, there are no distinct growth-ring zones (Fig. 1d), but trees sometimes form zonal layers, which are not identical with real growth rings.

In addition to the differences in structure, the three groups differ physiologically. In ring-porous wood, the latest growth ring fulfills the major task of water conduction, and consequently a new ring must be formed every year. In diffuse-porous woods and in conifer wood, previously formed growth rings participate in the water conduction. Hence, under adverse climatic conditions, the trees do not need to form a growth ring every year and may be characterized by absent or partially missing rings. Conversely, it is possible that two growth increments may be formed in a single year. These occurrences make the determination of growth

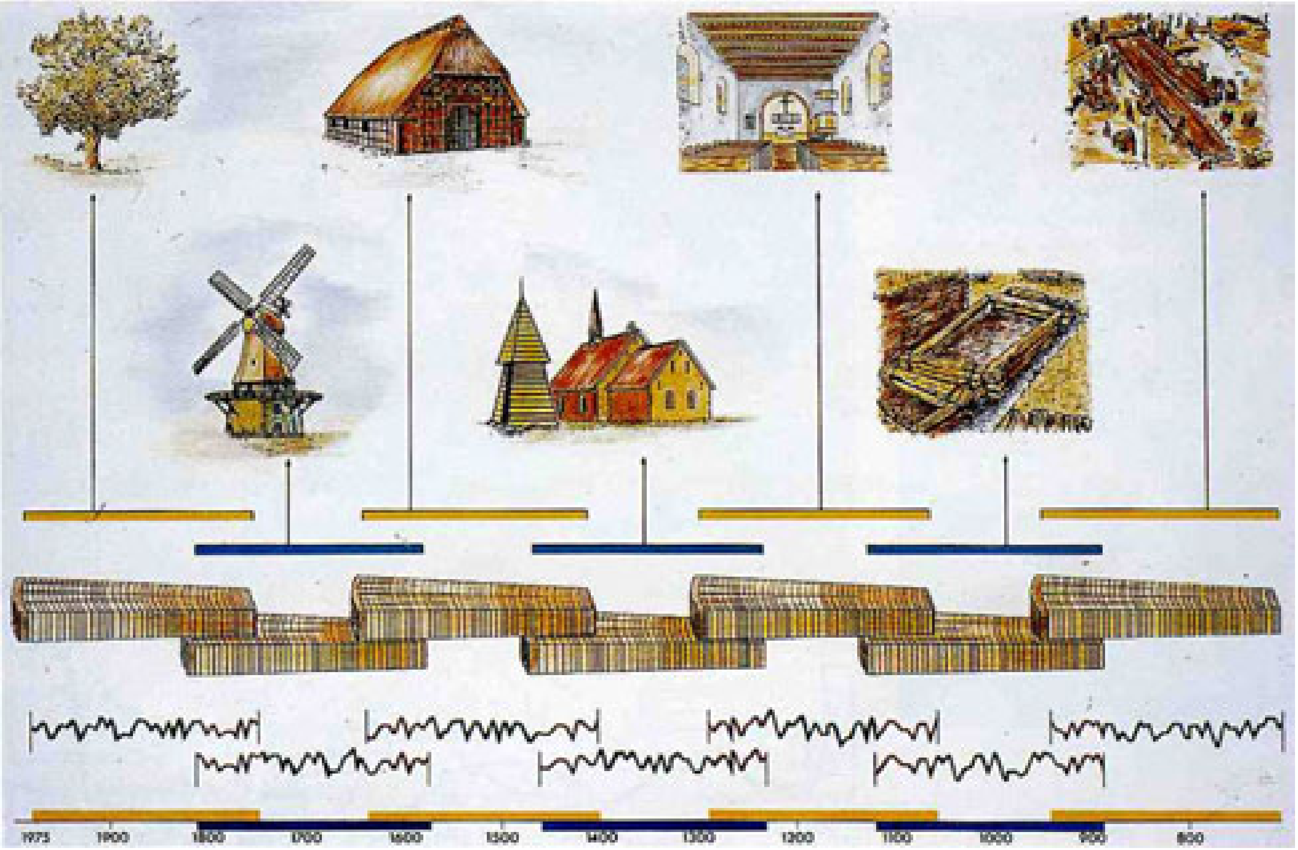


Figure 2
Overlapping system for the establishment of master chronologies.

rings and other dendrochronological work with diffuse-porous species more difficult than is work with ring-porous species such as oak.

The biological regularity of the ring series in trees of temperate zones makes it possible to date wood by comparing the sequences of undated wood with those of wood of known age. To establish comprehensive continuous growth-ring curves for periods longer than a tree's lifetime, it is necessary to use an overlapping system of individual curves (Fig. 2). An overlapping system is necessary for the establishment of these master chronologies, because trees in Europe do not normally live more than two or three centuries. Such standard curves exist, among others, for south and west Germany, several regions of north Germany, several areas in the Netherlands (partial), and the Baltic area, from which the wood for most Flemish and Dutch paintings was obtained (Fig. 3) (Eckstein et al. 1986).

Measurement and Cross Dating

To determine the ring widths in wood, a magnifying glass with an integrated scale may be used (Fig. 4a). This method is used if measurements have to be taken without laboratory equipment at the site. It is more convenient and faster to take measurements in the laboratory using a stationary binocular and a traveling stage on which the sample is mounted. These devices can be connected to a computer to record the data for immediate use in subsequent steps of the analysis (Fig. 4b).

Cross dating in its simplest form is the comparison of two tree ring sequences to determine if and to what degree they match, as well as to determine their placement in time to each other (Fig. 5). If one of the curves is attributed to a definite stretch of time, the positioning of the

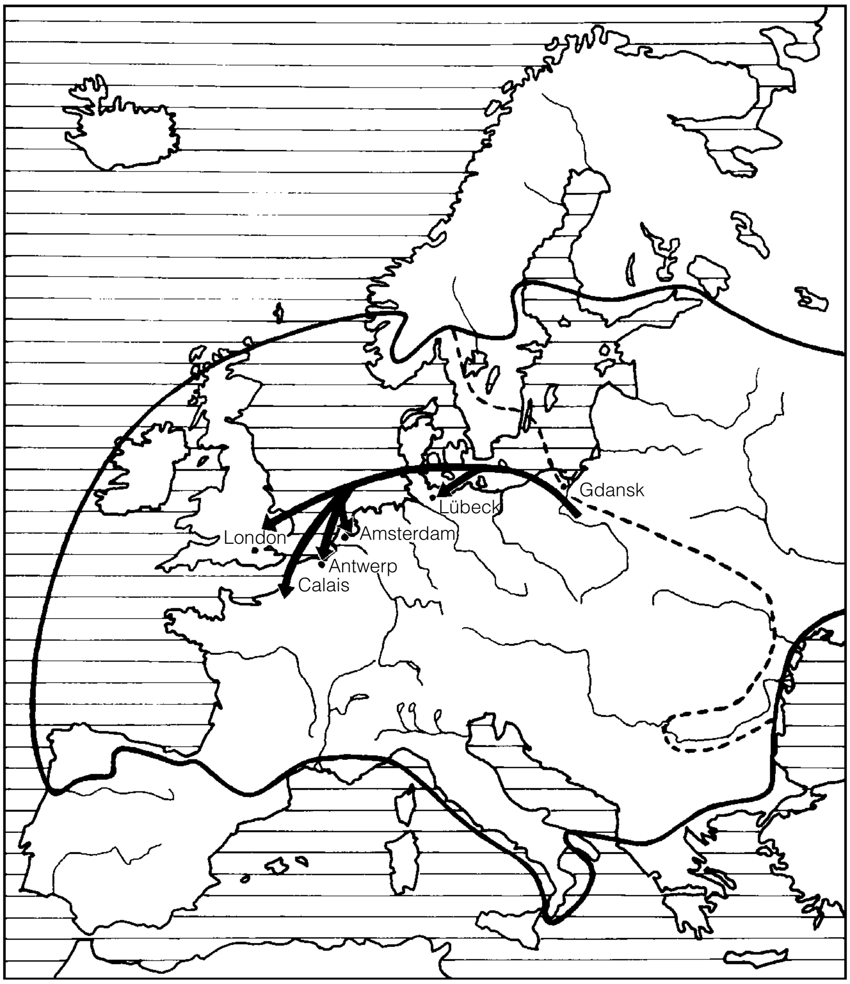


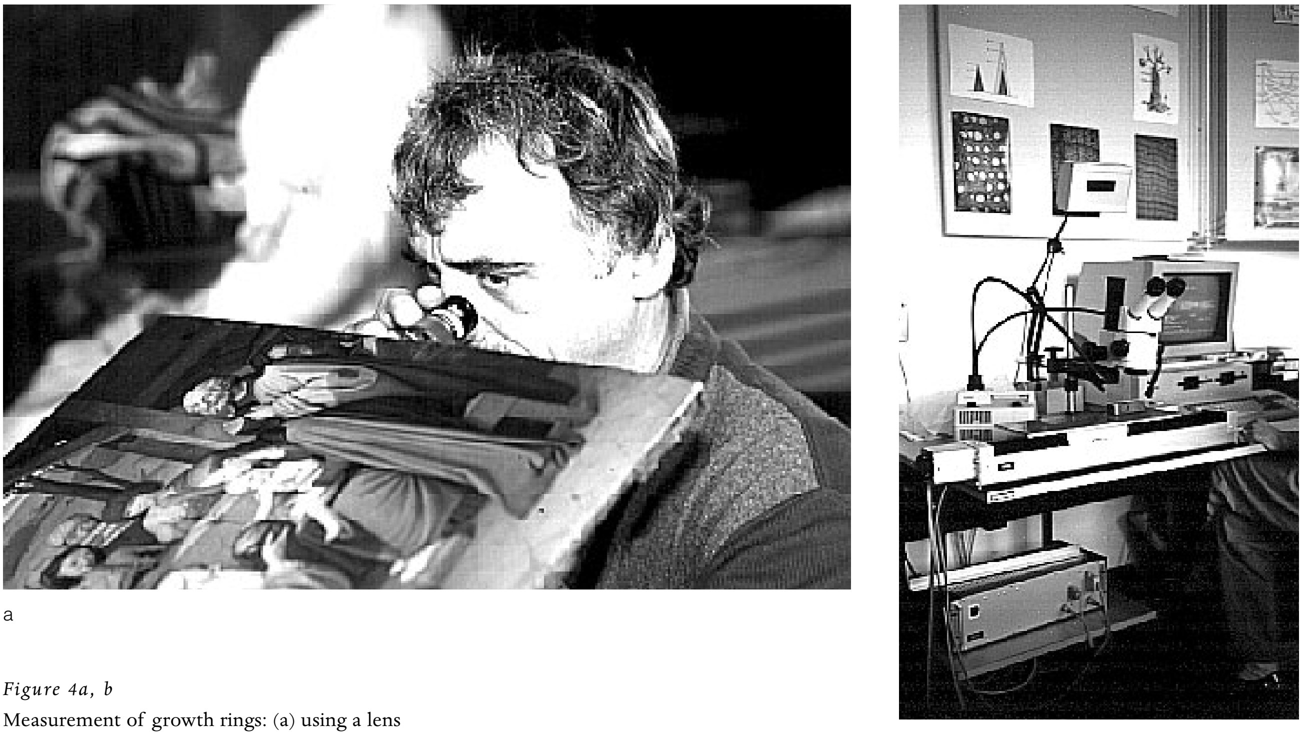
Figure 3
Areas of the natural distribution of oak. The distribution of *Quercus robur* L. (European oak) is shown as a heavy line; the distribution of *Quercus petraea* Liebl. (sessile oak) is shown as a broken line. European oak originates farther northeast than does sessile oak. The sources of oak timbers and the places of their use as panels are indicated by arrows.

second curve by maximum coincidence leads to absolute dating. For each kind of wood, a master chronology must be established for different geographical regions.

Problems

In the course of dendrochronological work, a number of problems involving the biological material and the methodology are encountered:

1. Conifers (such as spruce) or diffuse-porous broad-leaved trees (such as lime) may not even produce a ring in some years, thus preventing accurate dating because of the missing data.
2. Sometimes the state of conservation of a sample does not permit determination of the ring widths, as in the case of sapwood that collapses from excessive drying or that is destroyed by insects, bacteria, or fungi. In some cases, not even the number of rings can be determined.
3. For the cross dating of curves, one needs a minimum number of rings to obtain reliable results. Unfortunately, it is not possible to give a definite figure as the minimum. Even curves considered quite "long" sometimes do not provide the characteristic pattern necessary to date the curve. There are so many variables that sometimes dating is possible with as few as 50


a

b

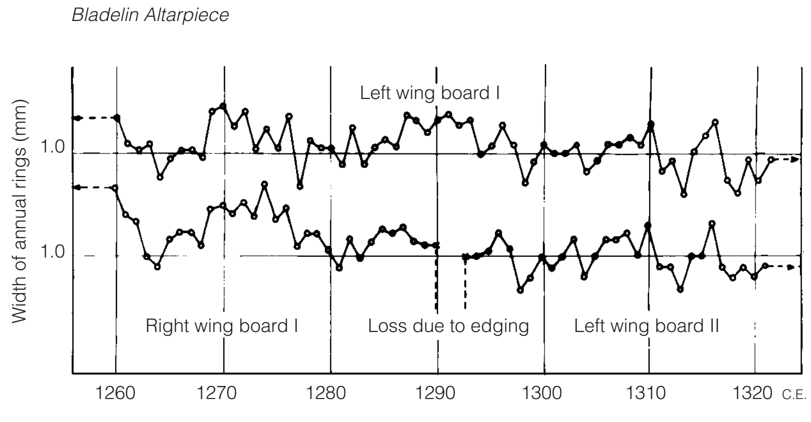
Figure 4a, b
Measurement of growth rings: (a) using a lens in the museum, and (b) using equipment for tree ring measurements in the laboratory.

tree rings, but in other cases even 200 rings may not be enough. The number needed, of course, depends mainly on the quality of the sample.

Sapwood Estimation and Seasoning

The final—and essential—result the art historian seeks is the identification of the year of tree felling. The last ring under the bark gives the exact date and even the season of tree cut, if it has been conserved. In preparing oak panels for paintings, panel makers usually cut the planks radially with regard to the cross section of the tree (Fig. 6). The bark and the light, perishable sapwood were removed, thereby eliminating evidence of the latest growth rings and making a determination of the exact felling year impossible, as only the latest measured growth ring of the panel can be determined to the exact year.

Figure 5
Comparison of growth rings derived from different boards of the Rogier van der Weyden *Bladelin Altarpiece*. Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie (inv. 535).



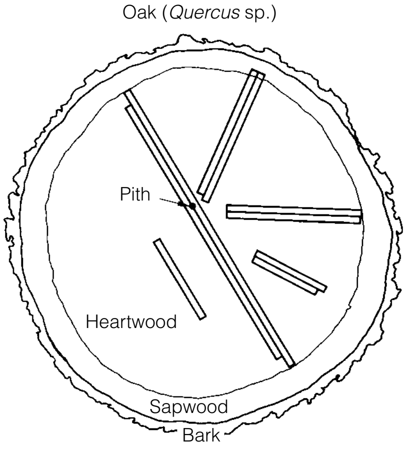


Figure 6
Various methods of extracting boards from an oak tree.

Furthermore, the statements below regarding the number of sapwood rings to be added are derived from statistical evaluation; each case must be considered individually. In addition to the dependence of the number of sapwood rings on the tree's age, the provenance of oak wood is also significant. In Europe, the number of sapwood rings varies from western regions to eastern regions (Hollstein 1980; Baillie et al. 1985; Eckstein et al. 1986; Kuniholm and Striker 1987; Lavier and Lambert 1996; Wazny 1990). With the elaboration of the new data (eastern provenance) for oak panels, new evidence for the sapwood allowance has to be accounted for. The number of sapwood rings found in trees from northern Poland was analyzed; all trees in the central 50% had 13–19 sapwood rings; the median value was 15, the minimum 9, and the maximum 36 (Fig. 7). For wood originating from Germany or the Netherlands, the median value was 17, with 50% of all values lying between 13 and 23.

To determine the earliest possible felling date, at least 7 or 9 sapwood rings (depending on whether the wood is of eastern or western origin) must be added to the latest growth ring found on the panel. Using the median, the felling date of the oak tree can be estimated with a span of −2 to +4 or +4 to +6. If a panel is made exclusively of heartwood, the felling date of the tree cannot be determined as precisely because there is always the possibility that an unknown number of heartwood rings were removed.

For beech (an all-sapwood species), however, the last growth ring available for measurement corresponds in many cases to the last ring formed in the living tree (and thus to the felling year). Usually, when panels were made of beech, the entire tree was used, except for the bark, which was removed. The same procedure can be verified for panels made from conifer wood.

The determination of the felling date also provides information as to the time the wood was seasoned before use in paintings. For oak panels of the sixteenth and seventeenth centuries, in most cases the interval between the felling of the tree and the creation of the painting has been determined to be approximately two to eight years (Bauch, Eckstein, and Brauner 1978). The few investigations carried out with signed and dated panels of the fifteenth century do not yet permit such an accurate estimate (Klein 1991). Instead, present studies regarding this period indicate a seasoning time of ten to fifteen years (Tables 1, 2), a finding that corresponds to the results of analyses obtained from fifteenth-century panels of the School of Cologne (Bauch, Eckstein, and Klein 1990). Similar investiga-

Figure 7
Distribution of the number of sapwood rings in oak trees from northern Poland.

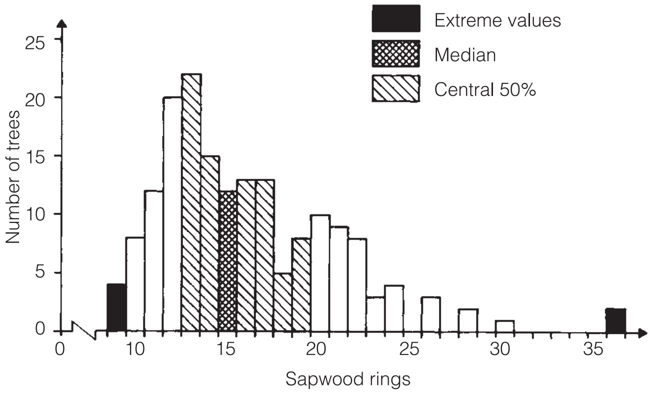


Table 1 Data relating to the determination of storage time for D. Bouts, *The Last Supper,* 1464. Oil on panel. Saint Pieter's Church, Louvain, Belgium.

	Minimum	Median	Maximum
Sapwood rings	9	15	36
Felling date	1445	1451	1472
Storage time (years)	19	13	—

Table 2 Data relating to the determination of storage time for J. Daret, *Adoration and Visitation,* 1434–35. Oil on panel. Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie (inv. 527, 542).

	Minimum	Median	Maximum
Sapwood rings	9	15	36
Felling date	1418	1424	1445
Storage time (years)	16	10	—

tions with sixteenth-century beech wood resulted in an estimated seasoning time of two to seven years, corresponding well to what holds true for oak wood from the same period (Klein and Bauch 1983).

Dendrochronological Dating

Notwithstanding the problems related to the determination of the tree's felling date and the seasoning time of the wood, dendrochronological analysis can be helpful for art-historical attribution. Dendrochronological analysis, however, can contribute definitive information only when the felling date is later than the art-historical attribution. When the felling date is earlier, either the board was cut from the center of the tree, or it had been stored for a long time, or the art-historical attribution is too recent. In all these cases, dendrochronological determination cannot give a precise solution.

Above all, it is more helpful for the attribution to analyze a group of panels, rather than a single panel, of a particular workshop. To that end, the dendrochronological department of the University of Hamburg has collected more than two thousand analyses of panel paintings since 1968.

The following sections examine the justification for the use of the dendrochronological method on oak, beech, and conifer panels from the fifteenth to the seventeenth century.

Oak wood

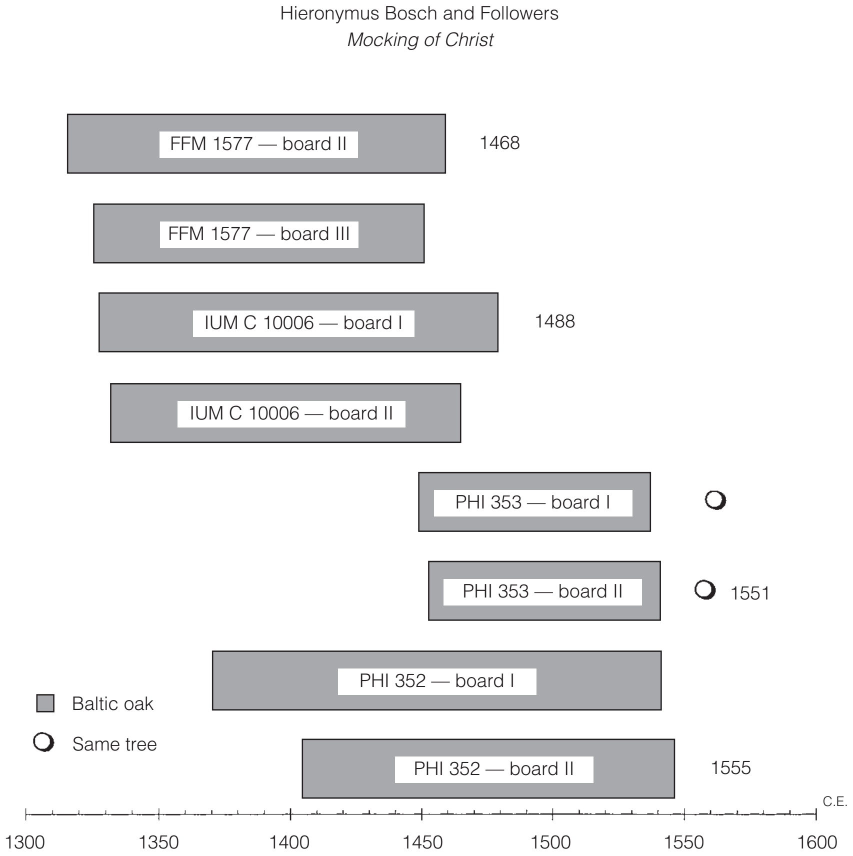
Oak wood was used nearly exclusively as a painting support from the fifteenth to the seventeenth century in the northern parts of middle Europe. Table 3 shows a survey of fifteenth- and sixteenth-century Netherlandish panel paintings; the results are reported elsewhere (Klein 1991, 1993, 1994a, 1994b). The wood was imported exclusively from the Baltic region by the panel makers.

Table 3 Survey of fifteenth- and sixteenth-century panel paintings of Netherlandish painters and workshops

Attribution	Number of panels
J. van Eyck	23
R. Campin	32
R. van der Weyden	61
P. Christus	19
D. Bouts	35
H. Memling	25
G. David	39
H. Bosch	39

Figure 8

Dendrochronological analyses of oak panels of Hieronymus Bosch (Frankfurt and Indianapolis) and followers (Philadelphia), with the same subject, the Mocking of Christ. (FFM = Städelsches Kunstinstitut und Städtische Galerie, Frankfurt; IUM = Indianapolis Museum of Art; PHI = Philadelphia Museum of Art.)



Regarding the paintings of Hieronymus Bosch, it is obvious that the dendrochronological analysis can differ between the original by Bosch and the later copies by his followers. The analysis of paintings with the same subject, the Mocking of Christ (Fig. 8), shows clearly that the two paintings in Philadelphia (inv. nos. 352, 353) were created in the 1560s. The felling dates of the painting panels in Frankfurt and Indianapolis lead to attributions in the lifetime of Bosch; nevertheless, a decision about an original can be finalized only by a critique of style.

Another example, shown in Figure 9, demonstrates that the copy of the *Garden of Earthly Delights* was painted in the middle of the sixteenth century, while the felling date for the original in Madrid corresponds with the art-historical attribution.

In the first half of the seventeenth century, the Dutch and Flemish painters used Baltic oak wood, but the Second Swedish-Polish War (1655–60) caused the total breakdown of the Hansa trade. Thus, Baltic timber is never found in panels made after 1650; oak boards from the forests in western Germany and the Netherlands were used instead. Tropical wood was seldom used in the seventeenth century; only in Rembrandt's workshop have different tropical wood species been identified (Table 4).

Dendrochronological analysis can prove that some boards originated from the same tree. Figure 10 shows, for example, five boards with an identical growth-ring structure. Furthermore, these boards have specific characteristics because they were cut off through the center of the tree

Figure 9
Dendrochronological analyses of oak panels of Hieronymus Bosch (Prado, Madrid) and a follower (private collection, Paris), both with the subject the Garden of Earthly Delights. (MA = Museo Nacional del Prado, Madrid.)

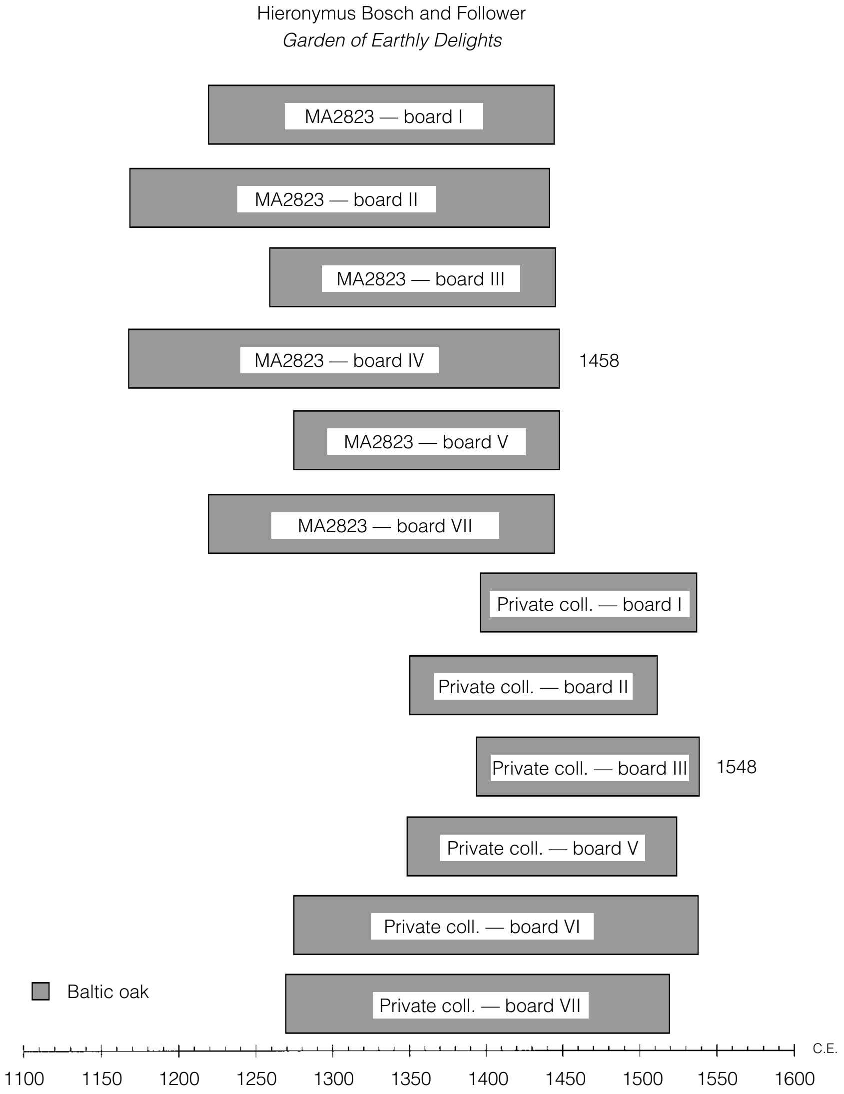
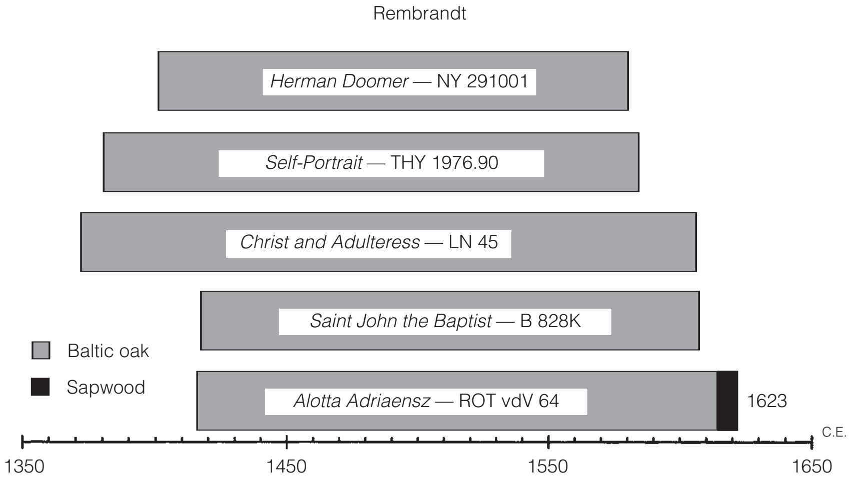


Table 4 Paintings of Rembrandt, with supports of tropical timber. (A = Rijksmuseum, Amsterdam; B = Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie; DET = Detroit Institute of Arts; DRD = Gemäldegalerie, Dresden; KSK = Staatliche Kunstsammlungen, Kassel; MP = Alte Pinakothek, Munich; NY = Metropolitan Museum of Art, New York; PET = Hermitage Museum, St. Petersburg; PL = Louvre Museum, Paris.)

Painting/Location	Art-historical attribution/ Signature	Wood species
Raising of the Cross (MP, 395)	attr. 1633	*Cedrela odorata*
Man Holding a Glove (NY 14.40.620)	sign. 164. [*sic*]	*Cedrela odorata*
The Holy Family (A, 4119)	attr. 1644	*Cedrela odorata*
The Visitation (DET, 27200)	attr. 1640	*Cedrela odorata*
Self-Portrait (KSK, 237)	sign. 1634	*Swietenia mahagoni*
Saskia (B, 812)	sign. 1643	*Swietenia mahagoni*
Susanna Bathing (B, 828E)	sign. 1647	*Swietenia mahagoni*
Christ at Emmaus (PL)	sign. 1648	*Swietenia mahagoni*
Young Woman (PET)	sign. 165(4)	*Swietenia mahagoni*
Old Man in a Fanciful Costume (DRD, 1567)	sign. 1654	*Swietenia mahagoni*
Anna Accused by Tobit (B, 805)	sign. 1645	*Cariniana legalis* or *C. estrellensis*
Joseph's Dream (B, 806)	sign. 1645	*Cariniana legalis* or *C. estrellensis*

Figure 10
Dendrochronological analyses of five oak panels of Rembrandt (all boards are from the same tree). (B = Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie; LN = National Gallery, London; NY = Metropolitan Museum of Art, New York; ROT = Museum Boymans–Van Beuningen, Rotterdam; THY = Coll. Thyssen, Madrid.)



and exhibit sapwood on both sides (see Fig. 6). These characteristics were found only in Rembrandt panels.

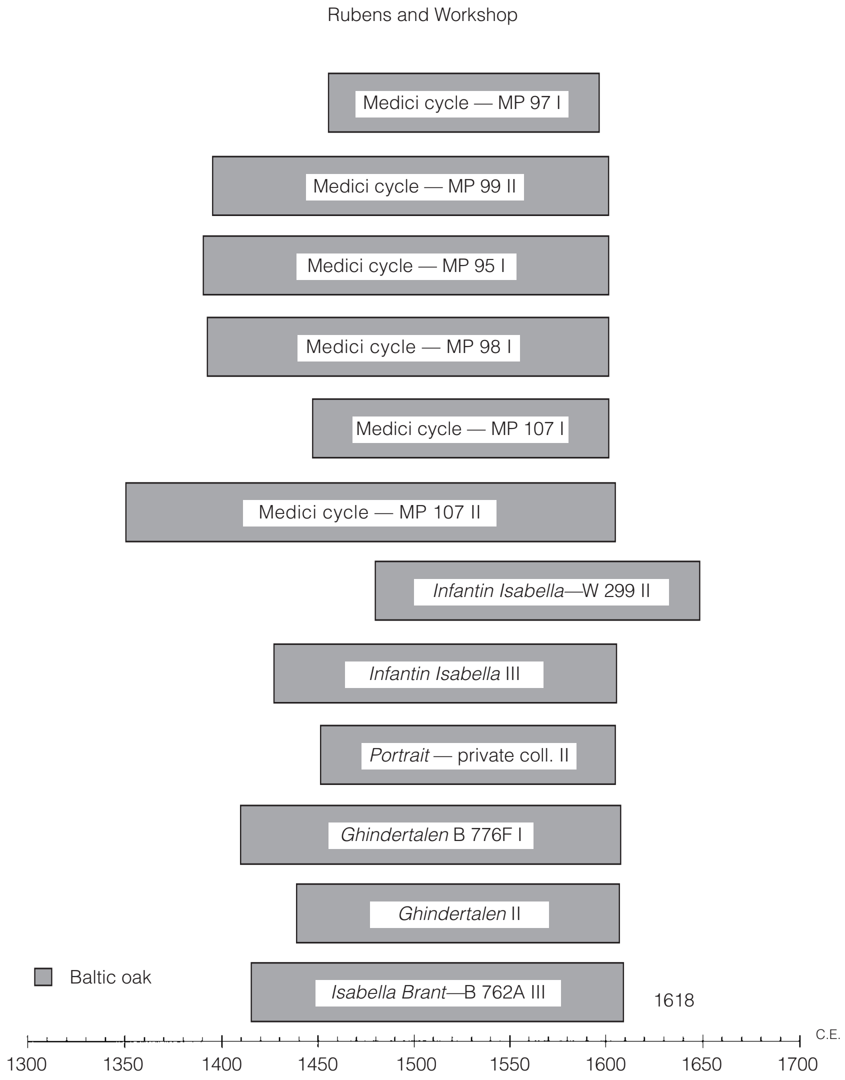
For Rubens and his workshop, it was proved that twelve boards from different paintings were fabricated from the same tree (Fig. 11). Most of the boards were used for the Medici cycle, which was ordered in 1621. By comparing the earliest felling date, 1618, with the order date, it can be surmised that the boards were seasoned only for a short time.

Beech wood

In central Europe, however, other woods—such as beech, lime, and poplar—and conifers were also employed for art objects. With reference to the experience gathered with oak, panels made of lime and beech wood from early German painters were also studied; dendrochronological dating was determined to be successful with the beech panels, while a chronology for limewood could not be established.

In historical times, beech was rarely used in construction; thus it has been impossible to establish a continuous chronology for dating beech panels up to the present. Such dating has been achieved in approximation, however, by comparative analysis based on oak chronologies. The positive results permit the absolute dating of the mean chronological sequence established from panels used by Lucas Cranach the Elder (1472–1553) and his associates. From the analysis of Cranach's signed and dated panels, it is clear that only a few years had elapsed between the youngest annual ring of each panel and its time signature. The determination of any given year, however, is limited to the last growth ring available for measurement. As has been discussed previously with regard to oak, it can be shown that boards from the same tree were used for entire panels or as parts of different panels (Figs. 12, 13). In comparison with oak panels, the number of boards extant from the same tree is extremely high for beech wood. This finding can be explained by the fact that beech wood panels were used only for a short time (1520–35) in the Cranach workshop and, furthermore, that beech wood was used (with some exceptions) only in the atelier of Cranach (Klein 1994c).

Figure 11
Dendrochronological analyses of twelve oak panels of Rubens and his workshop (all boards are from the same tree). (B = Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie; MP = Alte Pinakothek, Munich; W = Kunsthistorisches Museum Wien, Vienna.)



Conifer wood

To establish a chronology for fir, spruce, and pinewood, statistical measurements of chronological compatibility of recent trees within and between different regions were carried out, particularly for the forests in the northernmost and southernmost parts of Germany. In addition, panels of various conifer woods and the wood of stringed instruments were investigated at various museums in Europe and the United States (Klein 1990). For spruce wood, new chronologies were established and other existing chronologies used. For pinewood, a new chronology was established for northern Germany (Eckstein, Schubert, and Klein 1987). For fir wood, the establishment of a new chronology was unnecessary, because the chronology of Becker and Gierts-Siebenlist (1970) allows the dating of panels.

Spruce wood

The chronologies of spruce wood—originally established for dating stringed instruments—can also be used for dating panels. A chronology for the Alpine region, for example, has been successfully used to date several

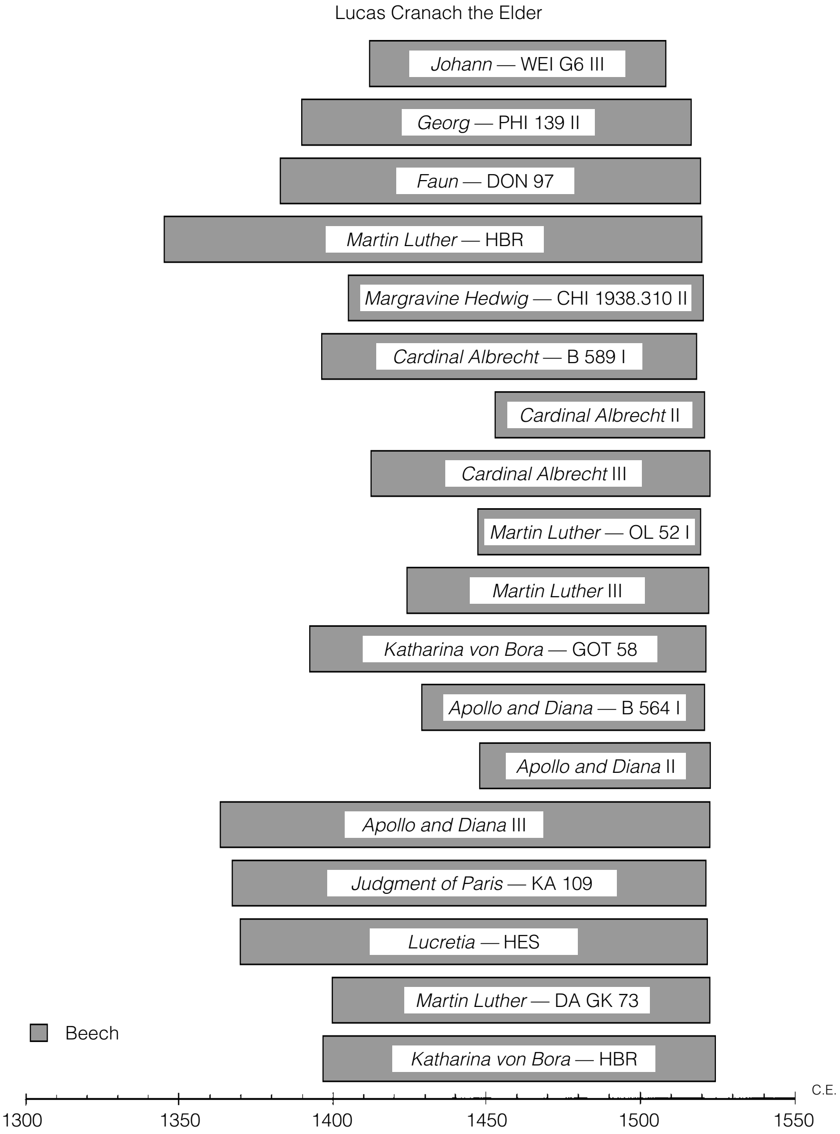


Figure 12
Dendrochronological analyses of beech panels of Lucas Cranach the Elder (all panels are made from the same tree). (B = Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie; CHI = Art Institute of Chicago; DA = Hessisches Landesmuseum, Darmstadt; DON = Coll. Fürstenberg, Donaueschingen; GOT = Schlossmuseum, Gotha; HBR = Roseliushaus, Bremen; HES = Sinebrychoffin Taidekokoelmat, Helsinki; KA = Staatliche Kunsthalle, Karlsruhe; OL = Landesmuseum für Kunst und Kulturgeschichte, Oldenburg; PHI = Philadelphia Museum of Art; WEI = Schlossmuseum, Weimar.)

panels of the cycle *Gray Passion* (Coll. Fürstenberg, Donaueschingen) created by Hans Holbein the Elder, as well as some boards from some altarpieces created by Hungarian masters (Fig. 14).

Fir wood

The fir chronology was used to date the following samples (Fig. 15). The panel *Maria Gravida* by the Master from Vienna contains six boards; the last ring indicates the year 1420. The art-historical attribution places the work between 1410 and 1430. When the seasoning time of the wood is considered, dendrochronology makes possible a more precise attribution of the panel to the mid-1420s. For the painting by a Hungarian master with an art-historical attribution of about 1490, the dendrochronological dating confirms the attribution, since the last growth ring is determined to be from 1472.

Conclusion

A large number of chronologies are available for several regions and time periods for the analysis of oak wood used for panels and carvings. Even so,

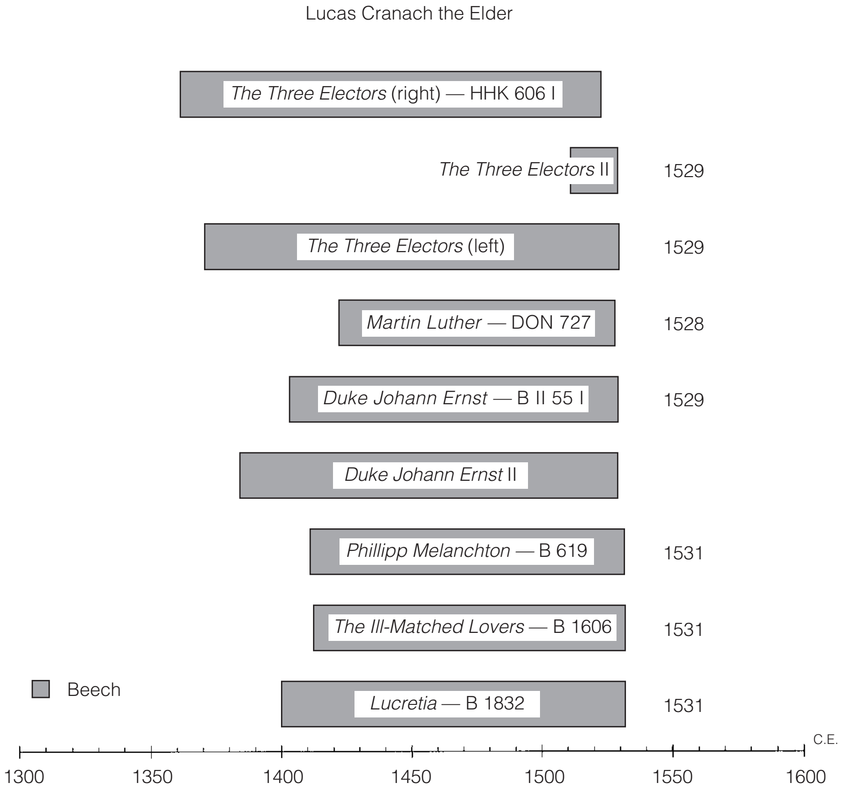


Figure 13
Dendrochronological analyses of beech panels of Lucas Cranach the Elder (all panels are made from the same tree). (B = Staatliche Museen zu Berlin, Preussischer Kulturbesitz, Gemäldegalerie; DON = Coll. Fürstenberg, Donaueschingen; HHK = Hamburger Kunsthalle, Hamburg.)

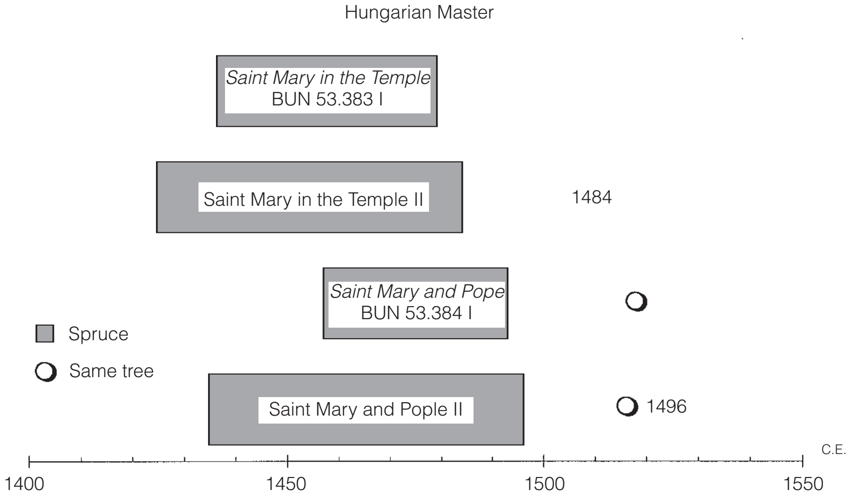
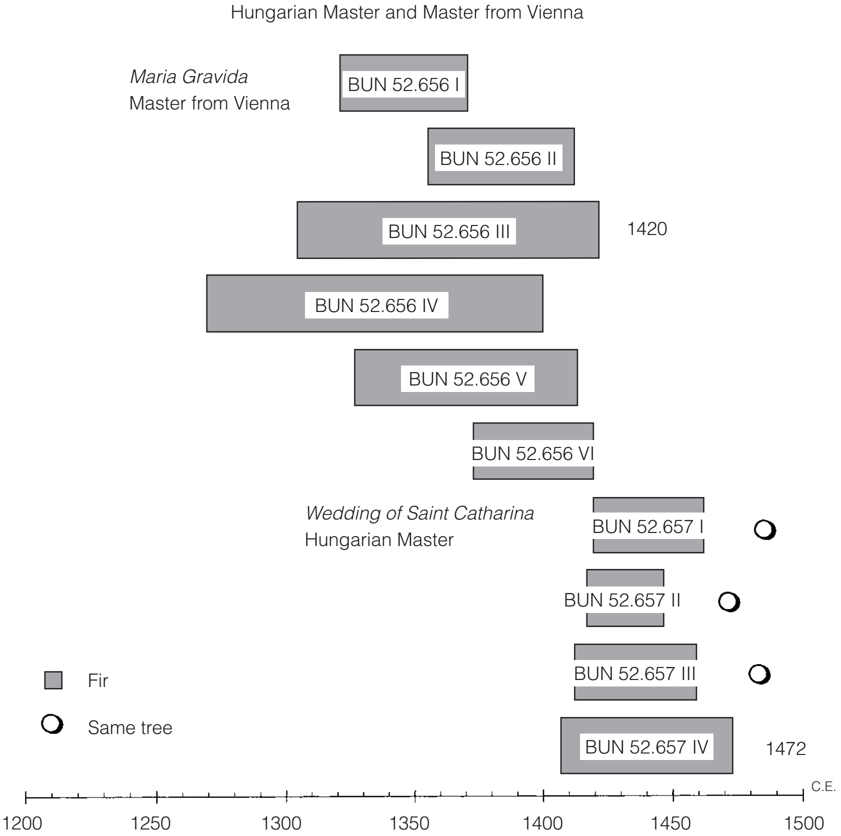


Figure 14
Dendrochronological analyses of spruce panels of a Hungarian master. (BUN = Magyar Nemzeti Galéria, Budapest.)

it is evident that the overall climatic conditions are often shrouded by local or regional influences, thus impeding the use of such general chronologies for dating particular objects.

The successful dating of beech wood widens the scope of tree ring dating in its application to wooden art objects and, at the same time, demonstrates the possibility that the use of dendrochronology may be extended to other diffuse-porous woods used for panels and carvings. Investigations into dendrochronological dating of poplar and linden wood are currently under way. Absolute dating of poplar is not yet possible because of the insufficient number of growth rings; in a few cases,

Figure 15
Dendrochronological analyses of fir panels of a Hungarian master and a master of Vienna. (BUN = Magyar Nemzeti Galéria, Budapest.)



however, a correlation between different boards originating from the oeuvre of one artist could at least be established. Analyses of linden wood initially showed more promising results, but at present, the irregularity of the growth-ring structure in individual trees impedes a successful establishment of master chronologies.

The biological investigations of panels and wood carvings can be helpful to the art historian, but they should always be interpreted along with results obtained by other methods. With regard to future research, the existing master chronologies must be completed. Furthermore, additional dendrochronological analyses with several kinds of wood from different centuries and regions are yet to be accomplished.

Acknowledgments

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Oldenburg; Hermitage Museum, St. Petersburg; Philadelphia Museum of Art; Louvre Museum, Paris; Museum Boymans–Van Beuningen, Rotterdam; Coll. Thyssen, Madrid; Kunsthistorisches Museum Wien, Vienna; Schlossmuseum, Weimar; as well as some private owners.

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A Guide to Wood Deterioration Caused by Microorganisms and Insects

Robert A. Blanchette

Deterioration inevitably occurs in all woods if environmental conditions are conducive to biotic or abiotic degradation processes. Environmental factors, especially moisture levels, are of paramount importance to the type and rate of decomposition. In terrestrial environments, a complex association of biological and chemical processes may cause extensive biomass loss within a very short time. A variety of biotic agents, including insects, fungi, and bacteria, work together to decompose wood. If decay-limiting conditions are imposed that exclude microorganisms and insects, wood can survive for exceedingly long periods of time.

Old panel paintings are subject to deterioration. Many forms of deterioration may affect painted wooden objects, depending on the environments where the artworks have been found or stored. The extent of damage is related to how well these objects have been protected from moisture, insects, microorganisms, and extraneous compounds. This article provides basic information about biological deterioration processes of wood, as well as a guide to the microorganisms and insects that attack wood, their mode of action, and the effect on chemical and physical properties of wood.

Wood is composed of cells that consist of cellulose, lignin, and hemicellulose. Mono- and disaccharides, aromatic compounds, inorganic substances, and other compounds are also present in varying amounts. The chemical as well as anatomical nature of wood varies greatly among tree species. Differences are seen in various cell types, amounts of extractive material, wood densities, and so on (see Hoadley, "Chemical and Physical Properties of Wood," herein). Sapwood, the outermost part of the tree's wood, which contained living cells while growing, may have high concentrations of free sugars, starch, amino acids, and proteins that make it highly susceptible to attack by some fungi and insects. In contrast, heartwood, the innermost region of the tree, often contains cells with accumulated substances that resist degradation. The heartwood of some trees—such as oak, walnut, cypress, redwood, and cedar—contains compounds that provide some degree of natural durability. Most of these compounds are phenols synthesized by parenchyma cells from carbohydrate precursors at the sapwood-heartwood transition zone (Hillis 1987; Fengel and Wegener 1984). These substances may diffuse into cell walls and fill cell lumina. Although some heartwood is very resistant to attack, prolonged exposure to adverse environments or the presence of aggressive

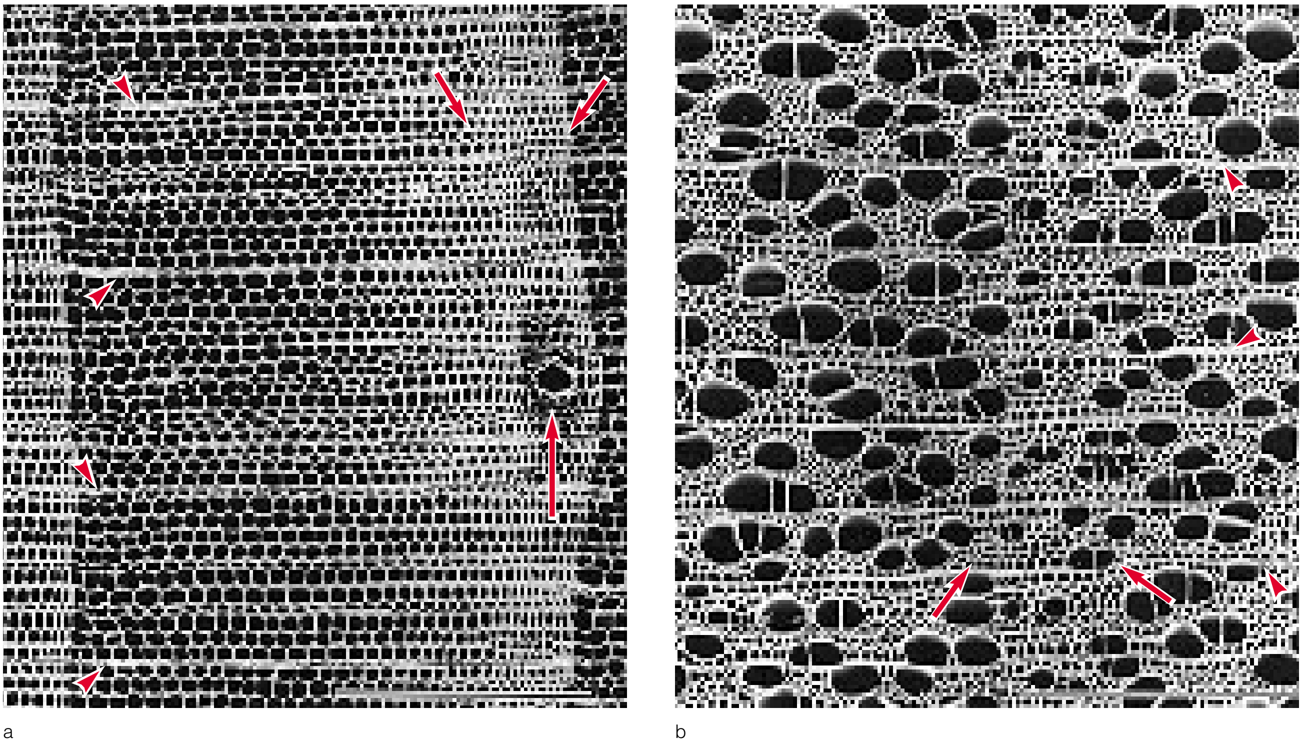


Figure 1a, b
Transverse sections of sound wood: (a) Spruce (*Picea*) showing earlywood and latewood (small arrows) tracheids, ray parenchyma cells (arrowheads), and resin canal (large arrow); (b) aspen (*Populus*) with large vessel elements distributed throughout earlywood and latewood regions (small arrows) surrounded by fibers and ray parenchyma cells (arrowheads). Scanning electron micrographs; bar = 500 µm.

heartwood-degrading microorganisms can result in substantial degradation (Blanchette et al. 1990; Blanchette 1992).

Anatomical characteristics of sound wood reveal great variation among tree species (Fig. 1a, b). Wood from coniferous trees (commonly referred to as softwood) is composed primarily of tracheids (90–95%). These cells have tapering ends that are closed. Transport of water and minerals is facilitated from one tracheid to another via pit apertures. Other cells include parenchyma cells and, in some species, resin canals. Wood from angiosperms (called hardwood) contains vessel elements, fibers, and parenchyma cells. Vessel elements have large lumina and cell-wall layers that differ from fibers. The middle lamella region of woody cells, found between cells, is highly lignified. The secondary wall layers are cellulose-rich regions, but they do contain some lignin. In general, softwoods have more lignin and less cellulose than do hardwoods. Additional and more detailed information on wood anatomy and chemistry can be found in writings by Fengel and Wegener (1984), Hoadley (1990), Miles (1978), Panshin and de Zeeuw (1980), and Shigo (1994).

Microbial Degradation of Wood

Fungi

Wood deterioration by fungi may occur from several sources. These include the following: surface molds that cause localized discoloration; stain fungi that penetrate deep into the sapwood causing blue, gray, green, red, or other dark coloration; and wood-destroying fungi that decompose cell-wall polymers (Table 1). In all situations, moisture is an important factor for spore (or other fungal propagulum) germination and for successful colonization of the substrate by the fungus. If the moisture content of the wood is below the fiber saturation point of approximately 28% (based on the oven-dry weight of the wood), there will not be

Table 1 Changes in wood due to degradation by fungi

Decay	Wood characteristics	Strength loss	Cell-wall components	Morphology
Brown rot (dry rot)[1]	Brown. Cracks and checks when dry, producing cubical fragments.	Large losses of strength in early stages of decay.	Cellulose depolymerization and loss.	Porous and shrunken cell walls, skeleton of altered lignified wall material.
Soft rot	Brown. Often localized to wood surfaces. Cracks and checks when dry.	Loss of strength in late stages of decay.	Cellulose degraded.	Cavities present in secondary walls, or secondary walls eroded, leaving only the middle lamellae.
White rot	Bleached appearance. Retains shape and composition until decay is advanced.	Major strength losses in intermediate to late stages of decay.	Lignin, cellulose, and hemicellulose degraded.	All secondary cell-wall layers and middle lamellae are eroded.
Fungal stain	Various discolorations in sapwood.	No strength losses.	Free sugars, nutrients, and wood extractives utilized; increase in melanin-like compounds and pigmented substances.	Preferential colonization of ray parenchyma cells; no cell-wall degradation.
Surface molds	Discolorations on wood surfaces only.	No strength losses.	Readily assimilated substances are removed.	Preferential colonization of parenchyma cells; no cell-wall degradation.

[1] *Dry rot* is a common term used to describe brown rot in some wood products.

sufficient free water available for fungal growth and development. The ideal environment for protecting wood from attack is often considered to be a relative humidity (RH) of less than 60%. In some modern museums, humidity can be well regulated; however, over past decades or centuries, many painted wooden objects have been subjected to environments conducive to fungal growth. The duration of this exposure and amount of moisture accumulation govern the type of fungus that may be established, as well as the extent of attack.

With current knowledge of wood-destroying fungi and their patterns of deterioration, it is possible to examine wooden cultural properties, determine the type of fungus that caused the damage, and identify typical characteristics for these forms of decay, such as microstructural damage to cells and loss of strength properties.

Three categories of wood decay are most commonly associated with wood that has been buried, entombed, or exposed to decay-promoting environments for a considerable length of time: brown rot, soft rot, and white rot (Table 1). For example, Fayum portrait paintings may have serious decay problems in parts of the wood, depending on the tomb environment and exposure to moisture (Martin and Reisman 1978). Panel paintings may show decay even if they have not been exposed to burial environments or are not thousands of years old. Painted wooden cultural objects from more recent times may be affected by poor storage conditions in damp cellars, churches, castles, country houses, or other highly humid environments. Since conservators may encounter a wide range of materials from different environments, all major forms of degradation by wood-decay fungi are presented below.

Distinct forms of decay are found in wooden materials because the enzymes and degradative mechanisms of different groups of fungi attack cell-wall components in different ways. As decay progresses, gross differences in color and physical characteristics are readily observed. Microscopic observations are required, however, to identify correctly the decay patterns in incipient to moderate stages of decay.

Brown rot

Brown-rot fungi cause a diffuse depolymerization of cellulose early in the decay process, resulting in significant losses in wood strength properties (Blanchette et al. 1990; Eriksson, Blanchette, and Ander 1990). In more advanced stages, wood polysaccharides are removed, leaving lignin chemically modified but undegraded. The resulting wood is a brown, lignin-rich substrate that cracks and checks into cubical fragments. Hyphae of the fungus colonize cell lumina and produce extracellular enzymes that diffuse throughout adjacent cell walls. Morphological characteristics show wood-cell walls consisting of a fragile network of residual lignin (Fig. 2a–d). These cells have little integrity and easily shatter into minute particles. Optimum wood-moisture content for brown-rot fungi ranges from 40% to 80% based on the oven-dry weight of the wood (Scheffer 1973; Zabel and Morrell 1992).

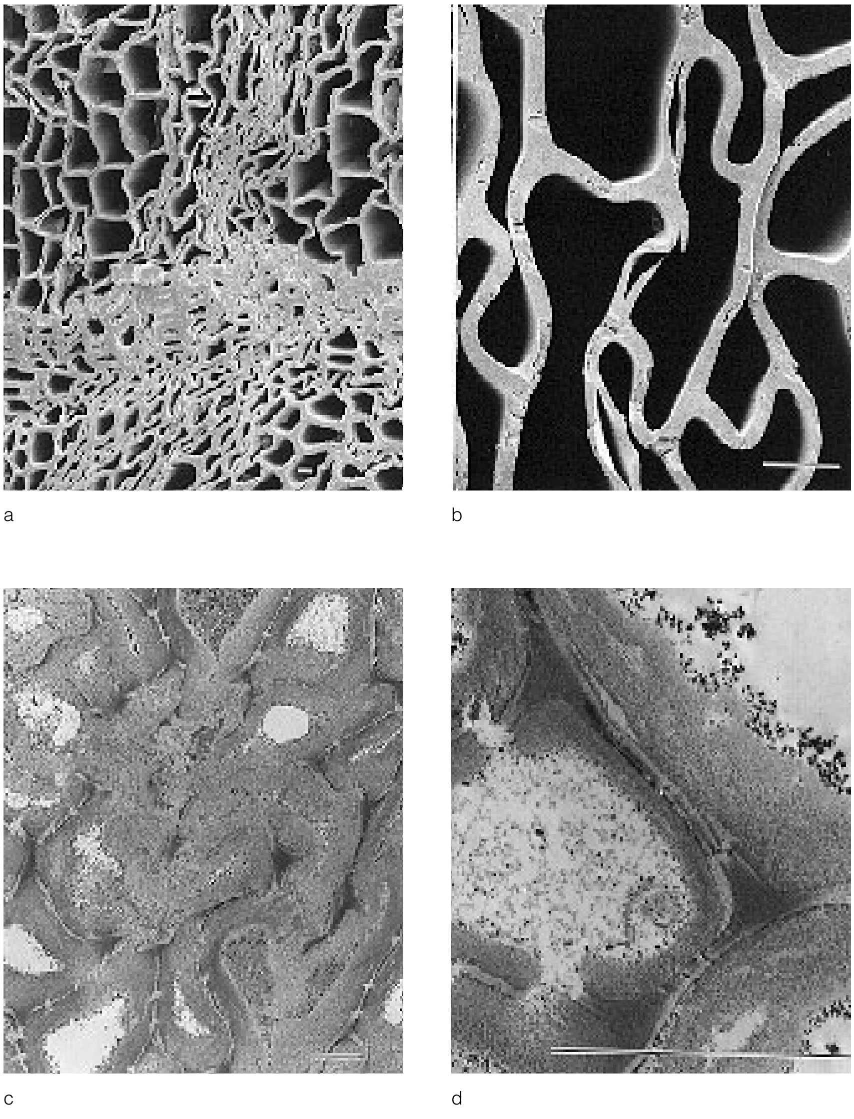

a
b
c
d

Figure 2a–d
Transverse sections of brown rot: (a) Collapsed and distorted tracheids are evident in spruce with advanced decay. The removal of cellulose has left a degraded cell wall that consists of residual lignin (scanning electron micrograph); (b) brown-rotted tracheids appear porous and have little strength and structural integrity left (scanning electron micrograph); (c) and (d) brown-rotted wood from the Statue of the Scribe of Mitry, V Dynasty (2340 B.C.E.), from Saqqara (Metropolitan Museum of Art, New York, MMA 26.2.4). Brown rot has caused the cells to disrupt into a fine mass of degraded cell-wall material. The residual lignin may fragment into dustlike brown particles. Transmission electron micrographs; bar = 15 μm.

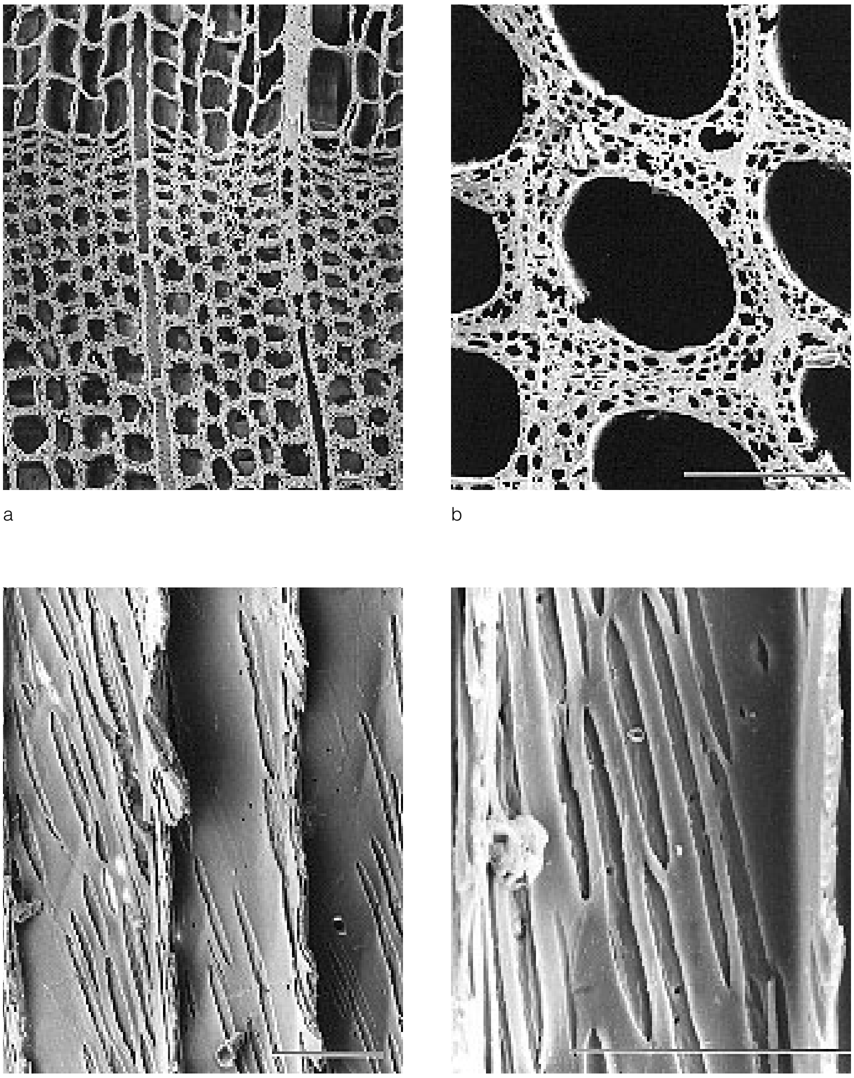
Brown rot frequently occurs in buildings in which wood products are in contact with a source of moisture. One of the most destructive fungi causing timber decay is *Serpula lacrymans*. This brown-rot fungus has the capacity to spread rapidly through wood and across nonnutritional surfaces (Jennings and Bravery 1991). Fungi that cause brown rot are a significant threat to the conservation of ancient and historic buildings. Brown-rot fungi are also responsible for the decay of wooden objects, such as those from ancient Egyptian tombs along the Nile Valley that were apparently affected by intermittent flooding or from other sources of moisture that migrated into the tombs (Fig. 2c, d). The severe compromise of wood integrity after an attack of brown rot presents difficult conservation problems (Blanchette et al. 1991; Blanchette et al. 1994). The extensive degradation of cellulose caused by these fungi leaves such an extremely weak framework of residual wall material that fragmentation occurs with only slight pressure or agitation (Fig. 2a–d). *Dry rot* is a common but inappropriate term that has been used instead of *brown rot*. Although the wood is often dry when found, moisture was needed for the decay to be initiated. The surfaces of older decayed wood usually crack and check when brown rot has been the degradative agent; the result is dried, cubical zones of brown wood.

Soft rot

Soft rot in wood often resembles brown rot macroscopically but differs remarkably in its microscopic characteristics. Soft rot may be localized to a shallow zone on wood surfaces or be more diffuse, depending on environmental conditions and the length of time over which decay has occurred. It may be associated with water-saturated environments or with relatively dry environments where lack of moisture or interacting alkaline conditions appear to inhibit other, more aggressive brown- and white-rot fungi (Blanchette et al. 1990; Blanchette and Simpson 1992). Microscopic observations of soft rot in many wood species reveal cavities within the secondary wall (Fig. 3a–d). Fungal hyphae colonize cell lumina and produce fine hyphae that penetrate into the cell wall. Once inside the wall, the hypha aligns its growth along the same axis as the microfibrils and initiates a localized degradation of the cell wall. In transverse sections, holes are observed within the S_2 region of the secondary wall (Fig. 3a, b). These degraded zones are actually chains of cavities with conical ends formed by oscillatory growth patterns from the soft-rot fungus (Fig. 3c, d). Cellulose and hemicellulose are extensively degraded, and some lignin is lost, but substantial amounts of modified lignin remain in the degraded wood. In some woods, particularly low-density hardwoods, another form of soft-rot attack may occur. The fungus enters cell lumina and progressively erodes all secondary wall layers from the lumen toward the middle lamella region (Blanchette et al. 1990; Nilsson et al. 1989). The middle lamella is not degraded, leaving a highly lignified framework of lamellae between cells. Significant strength losses are associated with advanced stages of soft rot, but reductions in strength during incipient to intermediate stages of decay are not well documented (Kirk and Cowling 1984; Zabel and Morrell 1992).

White rot

White-rot fungi have the capacity to degrade all cell-wall components (Fig. 4a–d). Preferential degradation of phenolic extractives, as well as of lignin, often results in a mottled or overall bleached-white appearance.



a b c d

Figure 3a–d
Decay by soft-rot fungi of pine (*Pinus*) from Tumulus MM, Gordion, Turkey (700 B.C.E.): (a) and (b) Transverse sections showing numerous cavities, characteristic of soft-rot attack, within the secondary walls of tracheids; (c) and (d) radial sections of tracheids exhibiting chains of cavities with conical ends formed within the cell walls. These cavities are not visible from the cell lumina until the very advanced stages of decay. Scanning electron micrographs; bar = 30 μm.

The fungus colonizes wood at an optimum moisture content of 40–100% (similar to conditions favorable for brown rot) and progressively erodes the woody cell wall. All cell-wall layers are eroded in the vicinity of the hyphae located in cell lumina (Fig. 4a). More advanced stages of decay show completely degraded cell walls adjacent to cells that are not extensively decayed (Fig. 4b, c). This localized degradation of some cells results in relatively small reductions in wood strength properties until moderate to advanced stages of decay occur. Some species of white-rot fungi have the capacity to remove lignin selectively from wood. The removal of lignin in the cell walls and middle lamella causes cells to detach and separate from one another (Fig. 4d). The remaining cells consist primarily of cellulose (Blanchette 1990).

Mold and stain fungi

Many opportunistic nonwood-destroying fungi colonize freshly cut wood by utilizing simple sugars and other readily available substances. Surface molds may discolor the wood with aggregates of pigmented hyphae and spores or extracellular fungal compounds that stain the wood cell walls (Table 1). Fungi commonly referred to as stain fungi may penetrate deep into the sapwood, preferentially colonizing ray parenchyma cells

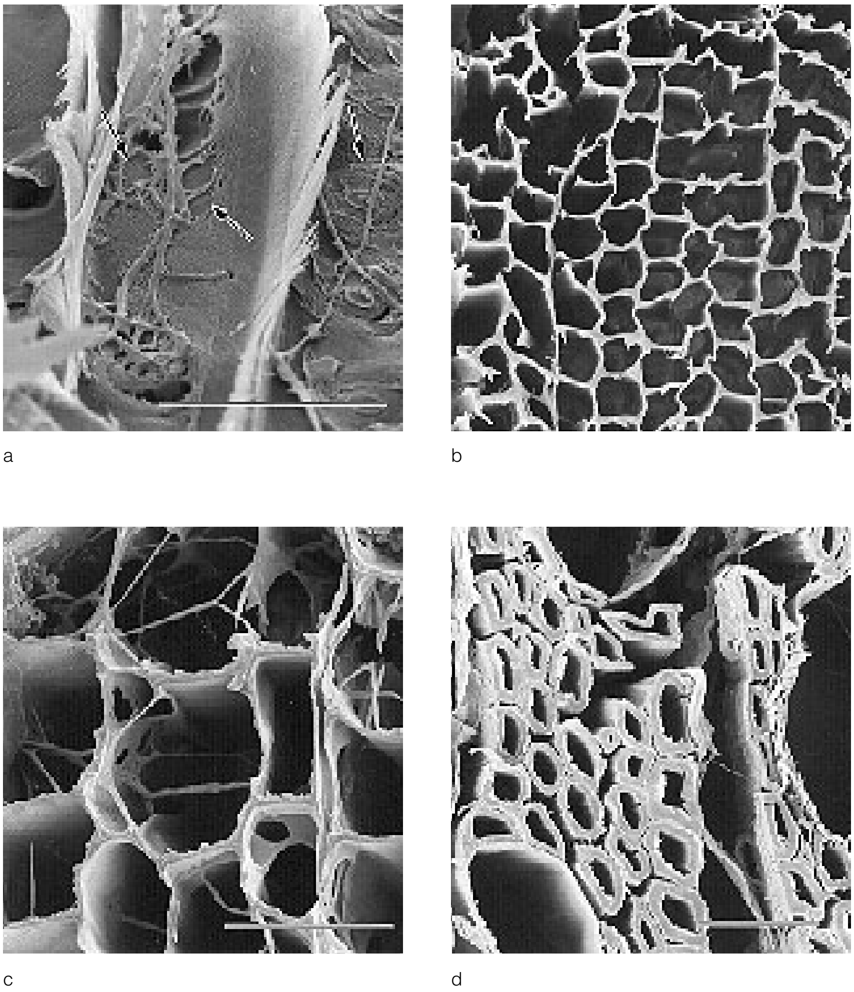


Figure 4a–d
Degradation of wood by white-rot fungi: (a) Tangential section showing fungal hyphae within tracheids causing a localized degradation of the cell walls around the hyphae (arrows); (b) and (c) transverse sections of eroded cell walls. The fungus degrades all wall components, resulting in localized erosion troughs and an overall thinning of cell walls; (d) delignification of birch (*Betula*) wood by a different species of white-rot fungus. Preferential degradation of lignin results in loss of the middle lamella between cells. The fibers and vessels, consisting of cellulose, readily detach and separate. Scanning electron micrographs; bar = 40 µm.

where stored nutrients are located. Since fungal growth follows the ray parenchyma cells, wedge-shaped staining patterns are evident when cross sections of the wood are examined. Stain fungi do not usually colonize heartwood.

Melanin-like compounds within hyphae or pigmented substances produced extracellularly cause blue, gray-black, red, brown, green, or other stains within the wood. Fungi that cause stains do not directly degrade wood cell walls, nor do they cause significant reductions in wood strength. Stains are usually considered detrimental to wood quality but have also been valued for their unique coloration. Green-stained wood, created by the fungus *Chlorociboria,* was selected by numerous artists in the fifteenth and sixteenth centuries for intarsia panels; the green-colored wood was used for rendering natural scenery with trees and floral leaves or for depicting book covers, fabric, or porphyry (Blanchette, Wilmering, and Baumeister 1992). The stain is not light sensitive and has survived many centuries without loss of color. Interestingly, remnants of fungal hyphae are still present in green-stained wood from several intarsia panels examined during recent restoration and conservation work (Blanchette, Wilmering, and Baumeister 1992).

Bacterial degradation of wood

Bacteria that cause deterioration in wood are most often associated with waterlogged conditions. Buried wood from wet terrestrial sites or from

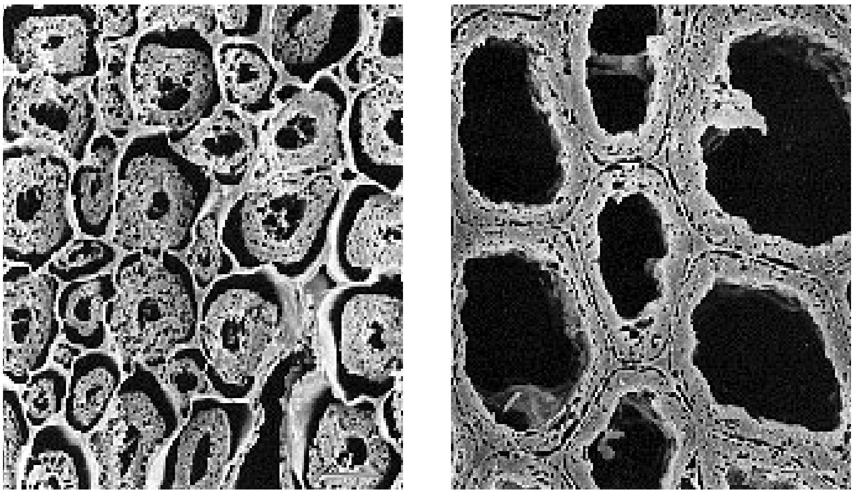


Figure 5a, b
Transverse sections of wood with bacterial degradation from the hull of the Uluburun, a late Bronze Age (1400 B.C.E.) shipwreck off the coast of Turkey: (a) and (b) Minute cavities caused by tunneling bacteria are present within the secondary cell walls. The residual wall matrix is porous and lacks integrity. The degraded wall material is disrupted during drying and is often pulled away from the middle lamella. Scanning electron micrographs; bar = 10 µm.

sunken ships in fresh or saline waters is usually severely affected by bacteria that erode cell walls or produce cavities or tunnels within the secondary walls (Fig. 5a, b). Other forms of bacterial attack include species that degrade membranes covering pit apertures but do not affect the cell wall. All of these bacterial degradation patterns are distinct from those produced by fungi and can be readily identified by examination with ultrastructural techniques (Fig. 5a, b). The exceedingly high moisture content and long exposure necessary for bacterial degradation suggest that this type of degradation would not typically be found in wooden panel paintings. Conservators who encounter waterlogged cultural properties may obtain additional information from writings by Blanchette and coworkers (1990), Blanchette and Hoffmann (1994), and Singh and Butcher (1991).

Insect Damage to Wood

General life cycle of insects

Damage to wood by wood-boring beetles (Fig. 6) results from the feeding stage of larvae (commonly referred to as woodworms) that bore circular tunnels ranging in size from 1 mm to 10 mm in diameter. The larvae feed on the wood, leaving fecal pellets and fine particles of wood in the frass. The common furniture beetle (*Anobium* spp.) adult lays numerous ellipsoidal eggs in surface cracks or along the rough end grain of wood (Fig. 7). After three to five weeks, larvae emerge from the eggs and eat their way into the wood with their strong mandibles. As the larvae tunnel through the wood, frass is often tightly packed into the gallery behind them. The larval period may last years, and a number of instar stages and molts occur before the larvae reach the pupal stage (Bravery et al. 1987; Creffield 1991; Hickin 1975). The size of the tunnels reflects the size of the growing larvae (Fig. 8a–c). Before pupation occurs, the larvae tunnel to the surface of the wood and form a chamber free of wood fragments and fecal pellets. Adults emerge after several weeks of pupation by boring an emergence hole out to the wood surface. The size of the tunnels, orientation within wood, and characteristics of the frass vary among the different beetle species (Table 2). The type of wood also may govern which wood-boring insect may attack. Some wood-boring beetles, such as powderpost beetles, require sapwood for successful larval development and do not infest heartwood. The *Lyctus* powderpost beetles have even stricter requirements that

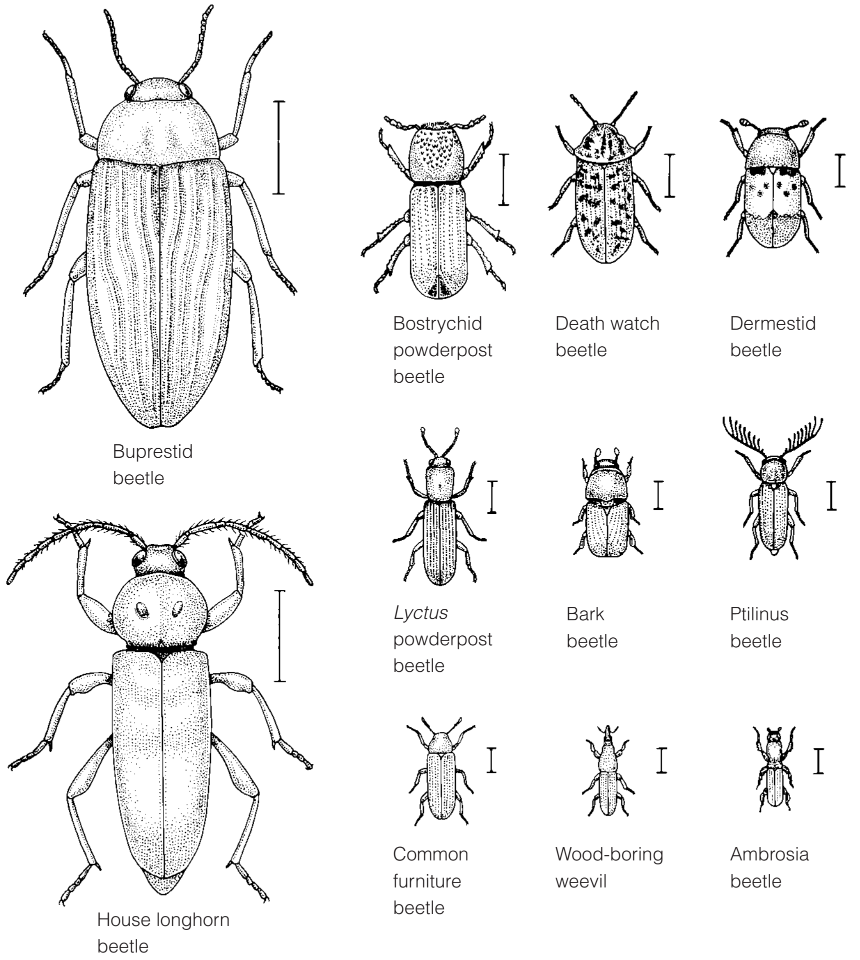


Figure 6
Common adult wood-boring beetles that can damage wood. The actual size of each insect is represented by the bar next to the beetle. See Table 2 for a summary of the woods affected and the distinguishing characteristics of the damage.

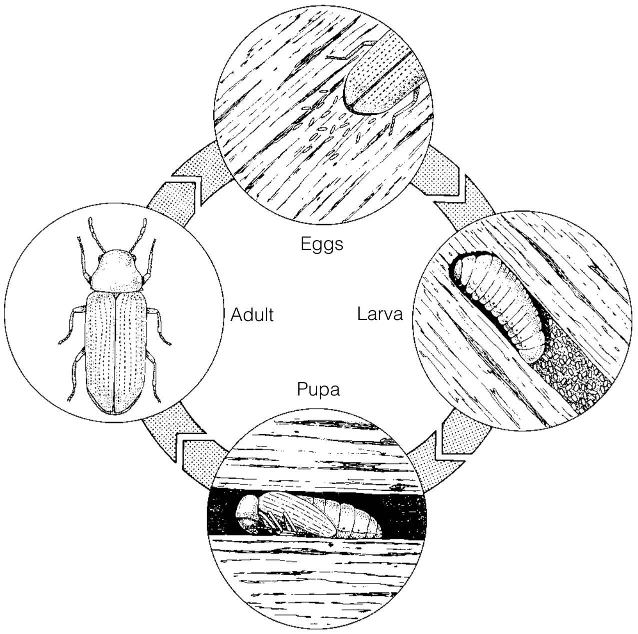
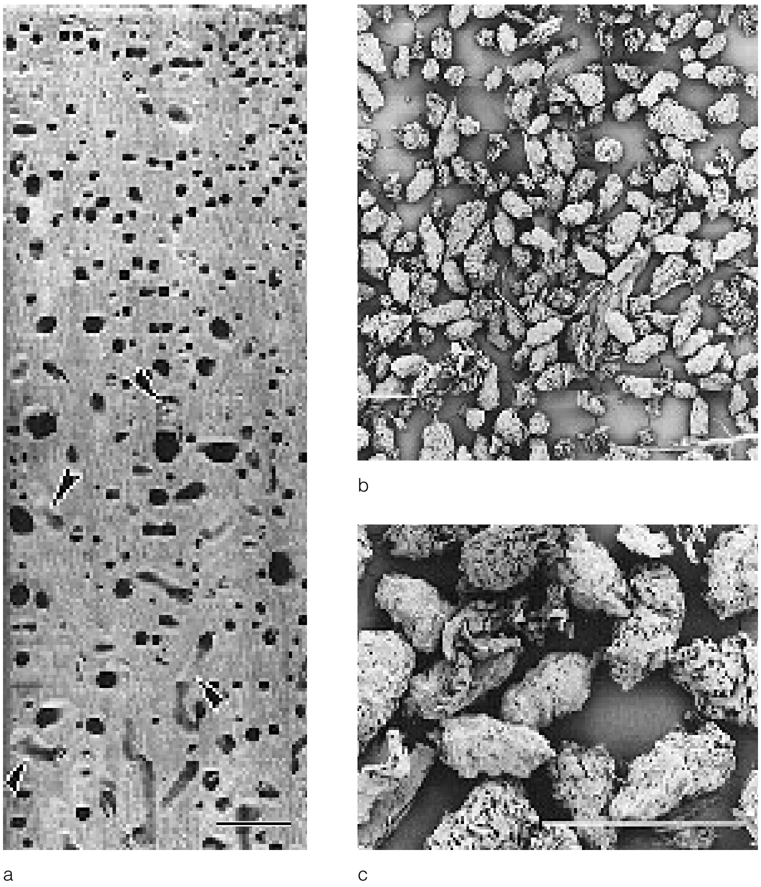


Figure 7
Life cycle of the common furniture beetle, *Anobium.* Eggs are laid on exposed wood. Larvae (woodworms) develop from eggs and bore into the wood, leaving pellets of frass and particles of wood behind. Larvae grow as they tunnel and feed on the wood. Larvae pupate before emerging as adults. Damage to the wood is due to the wood-boring larval stage of the beetle.

include wood with large vessel elements, such as oak and elm, and a high starch content (Hickin 1963, 1975). *Lyctus* beetles lay their eggs directly into vessel elements using a long ovipositor. The size of the ovipositor requires larger cells, such as the earlywood vessels of ring-porous woods, for successful penetration. Since eggs can be laid only in wood with vessels

Figure 8a–c
Insect tunnels and frass of the common furniture beetle, *Anobium:* (a) Cut wood from a stretcher (seventeenth century, Italy) with boreholes caused by the larval stage of *Anobium*. The size of the tunnel reflects the size of the growing larva as it feeds on the wood. Insect frass (arrows) is usually held within the tunnels (in this sample, however, it has fallen out during cutting); radially sawed wood, bar = 1 cm; (b) and (c) *Anobium* frass consists of pellets and fragments of wood. These small frass pellets are characteristic of *Anobium* attack. Scanning electron micrographs; bar = 250 μm.



of sufficient size to accommodate the insect's ovipositor, damage by this beetle is restricted to hardwoods with large vessel elements (Bravery et al. 1987), as well as bamboo and rattan, which have large vascular elements.

Moisture content is also an important factor for wood-boring insects. The *Lyctus* and *Anobium* beetles require relatively low wood-moisture levels of 8–20% for continued activity (Creffield 1991). However, damage can also occur and is often most severe in woods exposed to damp conditions. Other wood-boring insects, such as ambrosia and bostrychid beetles (Fig. 6), require a wood moisture of greater than 30%. Many wood-boring insects attack only wood that has been previously altered by decay fungi (Table 2).

Termite damage

Termite damage has been found to affect some panel paintings that were in direct contact with the walls of infested buildings in tropical regions (Boustead 1968), but otherwise this type of damage is not frequently encountered by museum conservators. Termites eat the interior portions of the wood, leaving a thin shell of exposed wood. Damage can be extensive and is easily recognized by the broad feeding galleries in the wood. Dampwood termites and some subterranean termites have a preference for moist wood and are often associated with wood in an early stage of decay by wood-rotting fungi. Galleries follow earlywood regions, leaving thin zones of latewood behind. Dry-wood termites also require moist wood but do not need an external source of water. A diagnostic feature of drywood-termite attack is fecal pellets that accumulate in excavated galleries of the wood. Galleries also lack orientation with the wood grain. A great deal of

Table 2 Summary of wood-boring-insect damage to wood

Insect	Wood	Distinguishing characteristics
Common furniture beetle, *Anobium*	Sapwood of softwoods and hardwoods; may attack heartwood if fungal decay is present.	Meandering tunnels 1–2 mm in diameter, often in direction of grain, filled with frass consisting of oval pellets and wood powder.
Lyctus powderpost beetle	Sapwood of hardwoods with large vessels, such as oak and elm.	Damage in sapwood with high starch content. Circular tunnels 1–2 mm in diameter, usually parallel to grain, filled with fine powder.
Bostrychid powderpost beetle	Sapwood of tropical timbers.	Convoluted tunnels 3–6 mm in diameter, packed with fine powder.
Wood-boring weevil	Decayed softwoods and hardwoods.	Tunnels 1 mm in diameter, oriented in direction of grain, with fine, granular powder.
Ptilinus beetle	Sapwood of hardwoods.	Meandering tunnels 1–2 mm in diameter, packed with fine bore dust.
Death watch beetle	Sapwood and heartwood of decayed hardwoods.	Tunnels variable in diameter from 0.5–3 mm, randomly oriented but common in direction of grain; bore dust consists of fine, disk-shaped pellets.
Ambrosia beetle, pinhole borer	Standing trees or cut green timber; does not infest timber that has been dried.	Main tunnel 1–2 mm in diameter at right angles to grain with short lateral tunnels originating from it; wood is darkly stained by fungi around tunnels; no bore dust in tunnels.
Bark beetle	Bark of hardwoods and softwoods.	Insects tunnel through bark and cause scoring of wood surfaces beneath bark and phloem; only found on fresh wood with bark.
Dermestid beetle	Damage to dry animal material (leather, fur, etc.); wood damaged only when in contact with a food source.	Short tunnels free from bore dust in wood adjacent to animal material; circular holes 3–4 mm in diameter and up to 10 mm long.
Buprestid beetle, jewel beetle	Standing dead or recently cut logs; rare in dry timbers.	Large tunnels 7–8 mm in diameter, with oval emergence holes; large cylindrical frass pellets make up bore dust. Larvae have large flat heads.
House longhorn beetle, cerambycid beetle	Sapwood of softwoods.	Tunnels 6–10 mm in diameter with similar-sized oval emergence holes; bore dust contains cylindrical pellets with fragments of wood; most of the sapwood may be consumed, with just a thin veneer of surface wood left.

information has been published concerning these wood-destroying insects in buildings and other wood products. For discussions of termite biology and attack, see Creffield (1991), Hickin (1975), and Moore (1979).

Control of Fungi and Insects

Successful control of fungi and insects requires knowledge of the biological agents that can cause deterioration, as well as the ability to diagnose the existing damage adequately. Once this information is available, much can be gleaned from existing literature about the nature of the attack and its effects on the wood.

A clean, pest-free environment with RH control of less than 60% is essential to prevent damage by fungi and insects. Reducing wood moisture halts decay activities by fungi but does not eradicate the fungus or the reproductive structures that produced it. A change in moisture and return to more favorable conditions for fungal growth can result in renewed growth of the dormant fungus or facilitate new infestations. An inspection program and the eradication of established insect infestations from wooden objects are necessary to prevent future damage. Although effective control procedures for insects are available that utilize fumigants, heat, freezing temperatures, or insecticides (Edwards, Bell, and King 1981; Hickin 1978; Nesheim 1984; Robinson 1988), these methods may not be ideally suited for use by museum conservators because of the side effects that may damage the object or because of safety concerns regarding the use of highly toxic substances and reactions (chemical or physical) that can affect the painted wood surface or other associated materials. Alternative strategies that include changes in atmospheric gases, such as high CO_2 or N_2 environments and oxygen scavengers, are being used for controlling insect pests (Daniel, Hanlon, and Maekawa 1993; Gilberg 1989, 1990; Hanlon et al. 1992; Pinniger 1991; Valentin 1993). Additional information on the use of modified atmospheres to eradicate insect infestations is presented by Hanlon and Daniel ("Modified Atmosphere Treatments," herein). Further testing of various control strategies in different substrates and deterioration situations is important in determining the most appropriate compounds, methods, and procedures to use. It is hoped that this review of the causal agents involved in the biological degradation in wood will serve as a diagnostic guide and source of information about the effects that different fungi and insects have on wooden cultural properties.

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Modified Atmosphere Treatments of Insect Infestations

Gordon Hanlon and Vinod Daniel

THE TRADITIONAL APPROACH to treating panel paintings infested with insect species has been to employ a range of toxic gases or chemical treatments to control or eradicate the infestation. However, over the last decade there has been a growing awareness of the environmental and health implications of using toxic gases or chemical treatments for pest eradication (Zycherman and Schrock 1988; Child and Pinniger 1987). Increased legislation in a number of European countries and in the United States has resulted in the restriction or outright banning of many toxic treatments. In addition, research has shown that toxic treatments can cause chemical change and damage to artifacts (Dawson 1988).

Insect damage to panel paintings is caused by several wood-boring species that lay their eggs on unpainted areas of the wood panel. During the life cycle of the insect, the larvae bore into the wood, forming tunnels or channels; the adults ultimately emerge through the characteristic round flight holes. This excavation of the wood ultimately undermines the structural stability of the panel, which, in turn, can undermine the surface paint layers. The wood-boring insects that commonly attack wood panels include the common furniture beetle or woodworm (*Anobium punctatum*), death watch beetle (*Xestobium rufovillosum*), powderpost beetle (*Lyctus* spp.), house longhorn beetle (*Hylotrupes bajulus*), and termite (*Cryptermes* spp.) (Schrock 1988). While a wide range of woods has been employed for the supports for panel paintings, the woods most commonly used in European panel paintings of the fourteenth to sixteenth centuries are poplar, oak, and walnut, which are all susceptible to insect attack.

To counteract insect infestation and the structural instability it causes, panel paintings have been treated with a wide range of toxic gases such as Vikane, ethylene oxide, and methyl bromide. Many chemical treatments have also been used and recommended in the past (Schiessl 1984; Serck-Dewaide 1978; *Museum* 1955). The liquid chemicals, applied by brush or injection, aim to kill any present infestation and have been recommended because they leave a residue that can prevent reinfestation. These chemicals include chloronaphthalene, mercuric chloride, Xylamon CombiClear, and arsenic salts. All of these chemicals are highly toxic, and in many cases, treatments with them will alter or affect the appearance of a painted surface. The residual effects of these chemicals may have health implications. There is even some doubt as to the effectiveness of some of these treatments (Hayward 1992).

Theory of Modified Atmospheres

As a direct result of concerns about the possible health risks, environmental impact, and damage to objects posed by toxic gases and other chemical treatments for controlling insect infestation, a growing number of research studies have investigated alternative treatments employing low oxygen environments. The stored products industry has used and published information on modified atmospheres to control insect pests in stored grains and food for several years (Bailey and Banks 1980). These studies, however, center on insect species that are not directly relevant to museum objects, and the aim of the studies is to control rather than to eradicate the insect infestation. More recent studies, which have focused on insect species that are known to be a problem for the museum community, discuss the effects of low-oxygen atmospheres on the mortality of several insect species (Valentin and Preusser 1990; Gilberg 1989, 1991; Rust et al. 1996; Valentin 1990). These investigations have shown the efficacy of low-oxygen environments—which use inert gases such as nitrogen, argon, and helium—to kill all life stages of the insect species studied and have quantified the relationship of temperature and relative humidity (RH) conditions to the mortality rate. A study sponsored by the Getty Conservation Institute was performed at the University of California, Riverside, where Rust and coworkers (1996) evaluated the mortality of all life stages of ten commonly found insect species at 55% RH and 25.5 °C in a nitrogen atmosphere having less than 0.1% oxygen. The time required for 100% kill varied from 3 hours for the adult firebrat (*Thermobia domestica*) to 192 hours for the eggs of the cigarette beetle (*Lasioderma serricorne*). Several independent studies have examined the mortality rates at low oxygen concentrations of wood-boring species, including the furniture beetle (*Anobium punctatum*), the powderpost beetle (*Lyctus brunneum*), the western drywood termite (*Incisitermes minor*), and the house longhorn beetle (*Hylotrupes bajulus*). All of these studies prove the efficacy of low-oxygen environments in killing the life stages of these species.

Based on this research, the Getty Conservation Institute and the J. Paul Getty Museum have perfected a number of methods for creating and maintaining a low-oxygen environment for the treatment of insect infestations. These methods are especially applicable to panel paintings and can also be used to treat infested picture frames and stretchers of canvas paintings. This article describes how these methods are applied to maintain an oxygen concentration of less than 0.1% and the desired RH for the duration of the treatment.

Practical Application

The two basic requirements for insect eradication using low-oxygen atmospheres are to create a method of encapsulating the object to be treated and to reduce the oxygen concentration within this enclosure to 0.1% or less.

Encapsulation of the infested object: Bag construction

The simplest method of encapsulating an object is to use plastic sheeting, which is heat-sealed to form a bag or pouch that encloses the panel to be treated. However, the oxygen permeability of various plastic sheeting varies considerably, and it is critical to select a plastic film with the lowest possible oxygen permeability to maintain the low-oxygen concentration within the bag for the duration of the treatment (Burke 1992). The authors selected Aclar (polychlorotrifluoroethylene) composite film with a permeability, or transmission rate, of 50 $cm^3 m^{-2}$ per day per atmosphere. Aclar is a plastic laminate sandwiched between layers of Mylar and polyethylene. Other plastic composite films are available with a lower oxygen permeability (such as Marvelseal), but these are either very expensive, unavailable in suitable sizes, or coated with an aluminized layer that prevents visual inspection of the object inside the bag.

Bags are fabricated by heat-sealing sheets of the Aclar plastic film (which has a heat-sealable inner coating of polyethylene) to create a bag or pouch that conforms to the shape of the object (Fig. 1). The seals can be made with a heated, handheld spatula or a clamping heat sealer. When the painting is placed into the bag, it is recommended that some form of spacer be used so that the bag does not rest on the painting's surface.

As a panel painting is essentially a two-dimensional object, even if the panel is enclosed in an integral frame, it is easy enough to construct a simple bag or pouch that closely conforms to the shape of the painting and is of a volume comparable to the panel painting. This results in an efficient enclosure for the subsequent reduction of the oxygen contained within the bag, whereas bags constructed for three-dimensional objects, such as furniture, are often much larger than an object's total volume.

Creating a low-oxygen environment

After the object has been encapsulated in an Aclar bag, the oxygen concentration in the bag must be reduced to less than 0.1%. As air is composed of approximately 20.9% oxygen, with the bulk of the remaining gases being nitrogen, the amount of oxygen to be removed or replaced is approximately 20% of the total volume of the bag. To produce and maintain the low-oxygen atmosphere, the bag is continuously purged with an inert gas such as nitrogen or with an oxygen scavenger, such as Ageless. Based on the studies by Rust and coworkers (1996), the authors recommend a treatment time of fourteen days at an oxygen concentration of 0.1%. This provides a safety margin, as the study found seven days to be the maximum time required to kill the most resistant species.

Figure 1
Heat-sealing of the Aclar plastic film to create a bag to encapsulate a panel painting for treatment.

To test the oxygen concentration within the encapsulating bag, the authors used the battery-powered Teledyne oxygen monitor (Model 320P). The monitor can be placed inside the transparent plastic bag, permitting the oxygen level to be read from the outside.

There are three methods for creating a low-oxygen environment:

1. *The static system.* This method is ideal for treating small objects, especially paintings. No purging of air in the bag is necessary. An estimated amount of an oxygen scavenger is inserted to absorb the oxygen in the bag initially and then to maintain the oxygen concentration at 0.1% for the fumigation period.
2. *The dynamic system.* An inert gas is used to flush all air out of the bag by an initial high flow rate. When an oxygen level of less than 0.1% is reached, the flow is reduced to the level required to maintain the low-oxygen atmosphere during the treatment period.
3. *The dynamic-static system.* The bag is purged with an inert gas (as with the dynamic system), but when the oxygen concentration has been reduced to 0.1%, the flow of nitrogen is turned off, and a predetermined quantity of an oxygen scavenger is inserted. The small opening in the bag for the insertion of the oxygen scavenger is sealed for the duration of the treatment.

Figure 2
Package of twenty-five sachets of Ageless oxygen scavenger.

The static system

The oxygen contained in the encapsulating bag is reduced to a low concentration by the use of an oxygen scavenger (Gilberg 1990; Daniel and Lambert 1993). The commercially available oxygen scavenger Ageless, which was used in this study, is described by the manufacturer as a mixture of finely divided moist iron (ferrous) oxide and potassium chloride (Fig. 2). Ageless is marketed in several different compositions that are used for a range of applications. The type used in this study was Ageless-Z, which is formulated to react rapidly and thoroughly with oxygen at an RH of 50% (Lambert, Daniel, and Preusser 1992; Grattan and Gilberg 1994). Ageless-Z is packaged in small, flat, paper packets and labeled as Z-100, Z-1000, and so on, to indicate the milliliters of oxygen that a single packet can scavenge. In most situations reported here, Ageless-Z-2000 was used. Because it can scavenge 2 l of oxygen, this size of packet minimizes the number of packets that need to be placed inside the bag.

When bags of Ageless are initially placed inside an Aclar bag, they scavenge the oxygen component of the air in the bag. Any oxygen that subsequently leaks into the bag must immediately react with the Ageless to maintain the low oxygen concentration in the sealed bag—that is, the leak rate cannot be greater than the rate of reaction of Ageless with oxygen. The leak rate refers to the amount of oxygen that permeates through the plastic into the bag.

This static system is ideal for panel paintings.

To treat an infected panel using Ageless, a bag is made out of Aclar plastic film, leaving an unsealed opening for the insertion of the Ageless packets. The Aclar bag should be constructed to be slightly larger than the object, to allow for the decrease in volume caused by the oxygen scavenging and to prevent any pressure from being placed on the painting by the bag. Once the bag is constructed, its approximate volume in liters

Figure 3
Placing oxygen-scavenger sachets into the encapsulating bag through the unsealed opening at the end of the bag.

is calculated. Approximately 20% of this volume is oxygen that can be scavenged by the insertion of an appropriate number of Ageless packets; however, it is recommended that double the calculated number of Ageless packets be inserted into the bag to provide a large margin of safety (Fig. 3). The unsealed opening is then heat-sealed and left for fourteen days (Figs. 4, 5). As the reaction of Ageless with oxygen is exothermic, the Ageless packets can become hot. It is, therefore, important that the packets not be placed on the painting's surface. The heat generated by the reaction is localized; in experiments, the temperature and RH within the bag remained constant.

Dynamic and dynamic-static systems

Both the dynamic and the dynamic-static systems use nitrogen gas supplied by a pressurized tank or nitrogen cylinder. The nitrogen gas is passed through a series of polypropylene tubes and delivered to the encapsulating bag, where it replaces the oxygen in the bag (Fig. 6). In this way the oxygen concentration in the bag is reduced to 0.1%. These two methods were developed for the treatment of larger objects (Hanlon et al. 1992; Daniel et al. 1993; Daniel, Hanlon, and Maekawa 1993). Both methods initially use the same procedure of flushing the bag with a high flow of nitrogen gas. As nitrogen gas that comes directly from a gas cylinder has a very low RH, it is essential to introduce a humidification system between the nitrogen

Figure 4, below
Final heat-sealing of the opening used to insert the oxygen-scavenger sachets into the bag.

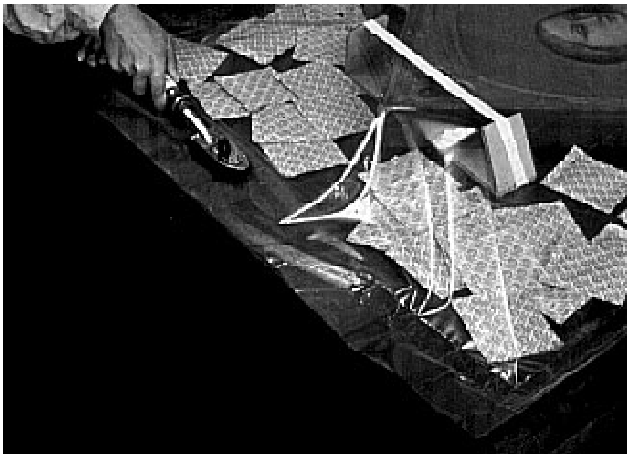


Figure 5, below right
Finished bag enclosing the panel painting to be treated and the number of oxygen-scavenger sachets calculated to reduce the oxygen concentration to 0.1%.

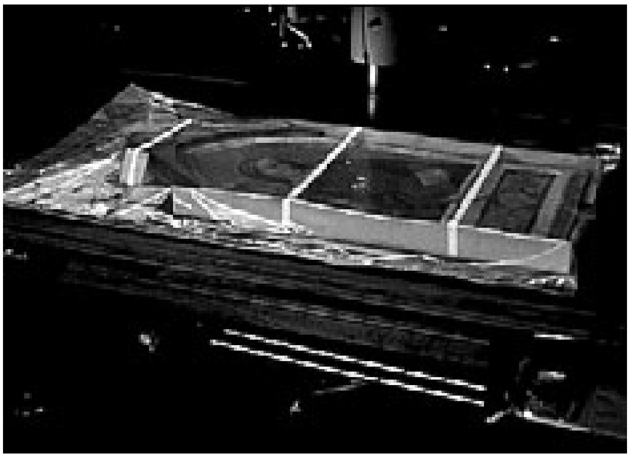
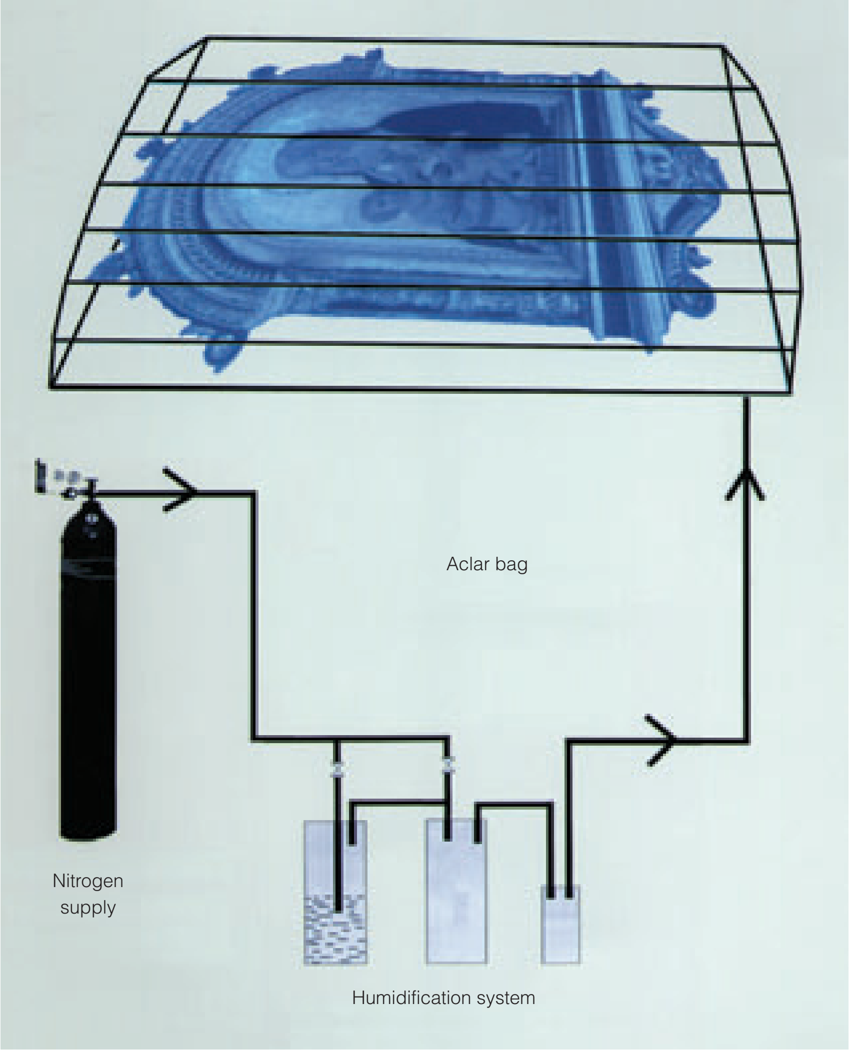


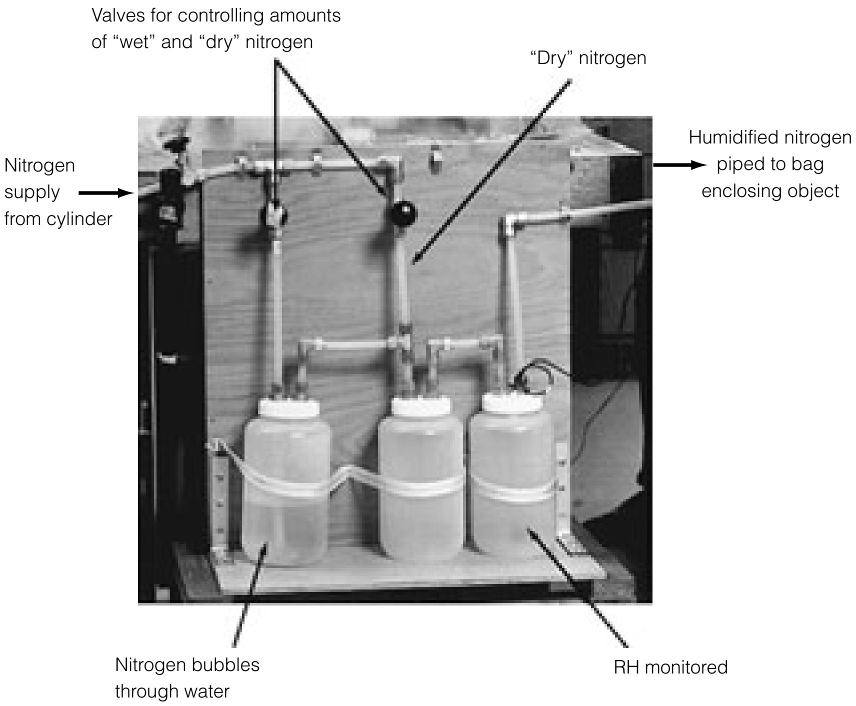
Figure 6
Schematic of the dynamic system for creating a low-oxygen environment.



supply and the bag containing the object. This allows the "dry" nitrogen from the cylinder to be humidified to the object's optimal RH before the gas flows into the bag. The humidification system functions by dividing the gas flow from the nitrogen cylinder into two valve-controlled lines. One stream of nitrogen is bubbled through water contained in a stout polypropylene bottle. The second stream flows directly to a second (dry) bottle, which is also connected to the water-filled bottle. The mixing of the dry and humidified gases is controlled by valves, which regulate the flow rate into each bottle. To monitor the RH of the resulting combined gas stream, a third bottle is used that contains an RH sensor and that also acts as a final mixing chamber before the humidified gas passes into the plastic bag containing the object (Fig. 7).

An important aspect of the design of the nitrogen-supply-and-humidification system is the use of leakproof fittings that minimize the influx of oxygen into the system. All fittings from the nitrogen cylinder to the entrance of the bag use $^{1}/_{4}$-in. (approx. 6 mm) brass O-ring-sealed Swagelok fittings. These fittings connect the polypropylene tubing, which is used to pipe the nitrogen gas from the gas cylinder, through the humidification system, and into the bag. Swagelok O-ring-sealed fittings are inserted into holes that are precisely drilled in the lids of the humidifica-

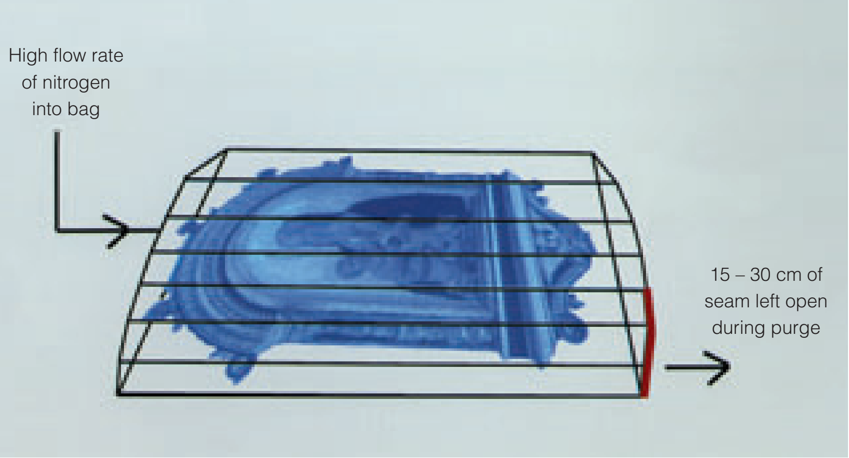
Figure 7
Humidification system for the nitrogen gas.



tion bottles and also connect the polypropylene piping joining the three bottles. A Swagelok fitting is also inserted into a precisely cut hole in the Aclar bag to allow the pipe to form a leakproof connection into the bag. A T fitting with an on/off valve is attached between the third bottle of the humidification system (which houses the RH sensor) and the bag. This allows the release of the nitrogen gas into the room atmosphere during the balancing of the humidification system, to produce the desired level of humidification of the nitrogen flow.

During the initial flushing at a high flow rate, the RH inside the bag should be constantly monitored. An opening of 15–30 cm is left unsealed and open on the corner of the bag opposite the nitrogen inlet to allow efficient mixing and flushing of the interior atmosphere without pressurizing the bag (Fig. 8). This opening is heat-sealed after the desired stable oxygen concentration is achieved.

Figure 8
System for purging the encapsulating bag with nitrogen gas to reduce the oxygen concentration to 0.1%.



In the dynamic system, once an oxygen concentration of 0.1% is reached, the nitrogen flow is decreased to a very low rate to maintain the low oxygen concentration. In contrast, in the dynamic-static system, while the nitrogen flow is still running at a high rate, the calculated number of Ageless oxygen-scavenger packets is placed inside the bag, the opening is heat-sealed, and the nitrogen flow is turned off. The Ageless maintains the low oxygen concentration by scavenging any oxygen that may leak into the bag.

Alternative Encapsulation Systems

Many museums own fumigation chambers purchased many years ago, designed for the use of toxic fumigants such as methyl bromide and ethylene oxide fluoride. In many cases these chambers can no longer be used because of environmental regulations against the use of these fumigants. Recently the Getty Conservation Institute converted the Los Angeles County Museum of Art's Vacudyne 36-ft^3 (approx. 1000 l) fumigation chamber (designed for ethylene oxide fumigation) to the dynamic nitrogen system described above. Several modifications were made to the existing mechanical and electrical controls to allow oxygen, temperature, and RH sensors to be installed inside the chamber. To operate the chamber, it is flushed with humidified nitrogen. Once the oxygen concentration drops to 0.1%, the inlet valve and the nitrogen flow are closed, and the oxygen concentration inside the chamber is monitored. With this particular chamber the leak rate was determined to be 50 ppm per day (0.005%). The chamber needs to be refreshed every eight to ten days to maintain the oxygen concentration below 0.1%.

Conclusion

The Getty Conservation Institute has sponsored an extended mortality study at higher oxygen concentrations (0.3%, 0.6%, and 1.0%) which is being conducted by Michael Rust at the University of California, Riverside. Results from this study so far suggest that an oxygen concentration of 0.3% is also effective in producing 100% mortality for the cigarette beetle (*Lasioderma serricorne*) and furniture carpet beetle (*Anthrenus flavipes*). This new research promises much easier implementation of low-oxygen atmosphere fumigation for insect eradication in the future.

The use of low-oxygen atmospheres for eradicating insect infestation is a viable alternative to toxic gas and chemical treatments. All commonly found museum pests can be eradicated by using a 0.1% oxygen atmosphere. The methods described in this article produce and maintain the RH and oxygen concentration at the required level. These methods are advantageous because they are nontoxic and low in cost and can be used in a variety of settings, such as galleries, storerooms, or conservation laboratories.

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Materials and Suppliers

Aclar (polychlorotrifluoroethylene) composite film, Bell Fibre Products, P.O. Box 1158, Columbus, GA 31993; distributed by Sealpak, 13826 Prairie Avenue, Hawthorne, CA 90250.

Ageless, Ageless-Z, and Ageless-Z-2000, Mitsubishi Gas Chemical Co., Mitsubishi Building, 5-2 Marunouchi 2-chrome, Chiyoda-ku, Tokyo, Japan; distributed by Conservation Materials Ltd., 100 Standing Rock Circle, Reno, NV 89511.

Marvelseal, Ludlow Corp., Lamination and Coating Division, 1 Minden Road, Homer, LA 71040; distributed by Sealpak.

Swagelok fittings (1/4-in. brass O-ring-sealed), Swagelok, 31400 Aurora Road, Solon, OH 44139.

Teledyne oxygen monitor Model 320P (battery-powered), Teledyne Analytical Instruments, 2049 Century Park East, Los Angeles, CA 90067.

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A Survey of Adhesives for Wood Conservation

Donald C. Williams

This article will provide a brief review of the types of adhesives used for wooden objects; the conservation treatment of wooden objects whose elements have undergone structural damage; and the selection and use of adhesives during conservation treatments. Whereas some of the adhesives discussed may not be suitable for panel paintings, it is important for conservators to be familiar with them because they are likely to be encountered in previous ill-advised conservation attempts on panels.

When reviewing the properties, selection, and use of adhesives for wood conservation, it is first necessary to answer the question What is the adhesive supposed to do? Equally important is the converse question, What should the adhesive *not* do? Naturally, this inquiry is part of the strategy of any particular conservation treatment and, in turn, involves the evaluation of any ethical issues facing the conservator.

Adhesives and Their Properties

Natural protein adhesives

Prior to the development of synthetic resin adhesives in the early twentieth century, the most common adhesive for wood—indeed, the glue dominant almost to the exclusion of all others—was protein glue. There are a number of glues that fall into this category of proteinaceous animal byproducts, such as casein, albumin, fish glue, and animal-hide glue.

Casein glue, a powder derived from the curds of acidified skim milk, forms a water-resistant and heat-resistant adhesive when mixed with water. Exceedingly strong, casein continues to be used for architectural laminae and was used in the past to butt-join panels during the original fabrication of panel paintings. Albumin glue, derived from blood proteins, is a water-resistant glue used since antiquity. For the ancients, the coagulating process, which drove the adhesion, required the use of fresh blood. However, when the process for making dried-blood glue was discovered in the early twentieth century, use of this adhesive became more widespread. Its primary utility was as a water-resistant, heat-activated adhesive for industrially produced plywood used especially in the fabrication of early wooden airplanes. Because of its prominence as a plywood adhesive, this thermoset glue is very often present as the binder in early plywood panels used as substrates for paintings. Fish glue, another traditional wood adhesive, is also a protein glue derived from the skins, bladders, and other by-products of the processing of fish for consumption. While the collagen derived from fish is very similar to that obtained from horses and other mammals, it tends to have a lower molecular weight and is therefore weaker and more easily soluble (Rose and von Endt 1984).

The protein glue used in the great majority of wooden artifacts encountered by the author is animal-hide glue. Through a heated aqueous extraction process, the protein collagen is removed from the hides, hooves, and sinews of mammals, primarily horses and cows, and purified to form gelatin or glue (Cummins 1986; Fernbach 1907; Perry 1944; Rose and von Endt 1984; Rosser 1939). Because protein molecules are broken down by heat, the temperature at which the collagen is extracted plays an important role in the characteristics of the adhesive. Collagen extracted at lower temperatures has a higher molecular weight and is stronger than collagen obtained from processing at higher temperatures. This characteristic is referred to as the gram-weight strength and is assigned by determining the weight necessary to depress the surface of a "glue jelly" by a specific amount according to a rigorously controlled protocol (DeBeaukelaer 1930; Fernbach 1907; Rosser 1939). In general, the gram-weight strength of glues normally used for woodworking is in the range of 200–300, although the range available is much broader (<100–>400). The procedure for preparing and using gelatin glues is based on the thermal and solubility properties of collagen, which is thermoplastic and water soluble.

Modifications of animal glue include the addition of plasticizers (usually glycerin or sorbitol up to 50% by dry weight), for flexibility and increased tack, and the addition of formaldehyde to yield a water-resistant, thermoset adhesive.

Probably the most important reason that hide glues are so widely used in the conservation of wooden artifacts is that they are almost completely reversible due to their water-soluble, thermoplastic nature. For many fabricators of wooden objects, this reversibility is not a factor, and the glue is used for other benefits, such as strength, ease of use, and availability. For the conservator, reversibility is a key consideration that becomes manifest in two principal areas. The first is the treatment of damaged or disassembled glue lines originally formed by hide glue. Manipulating, reforming, or removing the original material may be possible, as it was thermoplastic when applied and may remain so. The second benefit of this characteristic is retreatability, which is discussed elsewhere in this article. The structure of animal glues suggests a true chemical affinity for wood (von Endt 1986). Thus, their adhesion to a wooden substrate is excellent.

Animal-hide glue is hygroscopic, and its stability and properties are highly sensitive to environmental moisture. If the moisture level is too low, the glue becomes extremely brittle and can be fractured with very little applied stress, a circumstance that leads to failure of the bond line. If the humidity is too high, the glue softens and is susceptible to plastic deformation. In addition, an extremely high moisture level can result in an attack of fungi on the surface of the glue. For panel paintings that remain in—or are returned to—uncontrolled environments, this characteristic of animal glues must be weighed carefully when their use in conservation treatments of such panels is considered.

Natural resins

The use of natural resins as adhesives is not prevalent today; they are, however, encountered in historic objects.[1] Probably the most extensively used resin was shellac, a thermoplastic exudate of the bug *Laccifer lacca,* indigenous to India and Indochina. The resinous exudate is refined by a number of processes, including heat, solvent, and aqueous extraction, resulting in an amber-orange material of varying purity and composition, depending on the specifics of the refining process. From the experience of the author, shellac was primarily used to glue nonwood veneers to a wooden substrate.

Shellac is normally used in solution with alcohol and dries by solvent evaporation, although it can be used as a pure material liquefied by heat only. It is relatively incapable of resisting thermal or chemical attack, but under the proper conditions, it can remain stable indefinitely.

Contact adhesives

Contact adhesives form an immediate strong bond and therefore are also called *contact cements*. Contact adhesives include both natural and synthetic rubber in solution. They are thermoplastic and can be softened with heat and/or organic solvents.

Due to their primary function as laminae adhesives, the most common application of these adhesives is to glue wood or other veneers to a substrate. They may also be encountered in an earlier, inept repair to structural elements. These adhesives do not appear to be exceptionally stable over a long period of time (Feller and Encke 1982). Deterioration of the adhesive results in the delamination of the fabricated structure.

Synthetic resin adhesives

Emulsions

The most widely used general-purpose glues in the wood crafts today are those based on aqueous emulsions of polyvinyl acetate (PVA) and are commonly called “white” glues. Some closely related adhesives generically called “yellow,” “aliphatic,” or “carpenter’s” glues may also be used. These water-based emulsions are opaque white or yellow liquids that become translucent when dry. Depending on their formulation and environmental influences, these adhesives can remain stable for long periods of time, as well as remain soluble and reversible to some degree.

PVA emulsion is the most common adhesive used for fabrication in contemporary woodworking. It is also used with moderate frequency in conservation. When the need arises, PVA and other emulsions bond well to hide glues.

In many respects, acrylic emulsion adhesives are much like PVA emulsion in appearance, use, and hardening mechanisms. While not widely used in the nonindustrial fabrication of objects, acrylic emulsions are used in conservation for the same applications as PVA emulsion. The advantage of acrylic emulsions is that they can be obtained in a wide variety of formulations with specific properties, such as molecular weight ranges and solubility characteristics for a hardened film.

Solutions

Synthetic resin solution adhesives are not widely used for fabrication in woodworking, but they remain a vital tool for the conservator.

A wide range of synthetic resins is available, and individual acrylic resins (or blends) possess particular characteristics. Of these properties, the two most important are solvent specificity and long-term stability. Resin solutions are themoplastic solutions that dry through solvent evaporation and, depending on the formulation, can remain resoluble for a longer period of time. The stability of certain acrylics has been well documented in conservation literature.

Two synthetic resin adhesives—cellulose nitrate and cyanoacrylate—are not used today for conservation but may be encountered in earlier, inept repairs. Cellulose nitrate adhesive is a solution of nitrocellulose and other film-forming materials in a mixture of organic solvents. This adhesive dries solely through solvent evaporation. Cellulose nitrate is not very effective as a bond-forming material with wood and therefore is almost never used as a primary adhesive in wooden objects. It is an unstable material unsuitable for use in the conservation treatment of any wooden artifact (Koob 1982; Selwitz 1988). Cyanoacrylate hardens quickly through an anaerobic chemical reaction with nitrogen in the atmosphere. Brief working time, poor adhesion to wood, and long-term instability render it unsuitable for use by the wood conservator.

Hot melts

While most thermoplastic materials could be broadly classified as hot-melt adhesives (e.g., hide glue, which begins to harden by cooling, and shellac and acrylics, which can be used as melted resins), this section will touch on those materials specifically designed to be used in a molten state and that harden solely by cooling. Hot-melt adhesives, as defined in this section, come in a wide variety of compositions the formulations of which can be very specific regarding the properties of the adhesive, not only in a solid but also in a liquid state (Gutcho 1983). Because these adhesives must often be heated to well above room temperature for them to flow, and because they solidify by cooling, their use is limited to the penetration possible in a very brief period of time.

Hot-melt adhesives are becoming increasingly important in the industrial fabrication of wooden objects and are beginning to be used in the conservation of historic wooden artifacts. However, knowledge of hot-melt adhesives within the conservation field is limited, and little critical study has been made of their long-term stability and other properties.

Multiple-component reactive adhesives

Thermosetting, multiple-component adhesives are likely to be encountered by the conservator only in previous, ill-advised repairs. These materials, which harden by the chemical reaction of the various components, include urea-formaldehyde resin, epoxies, and phenolics.

Multiple-component reactive adhesives possess great strength under a wide variety of conditions and can be virtually impervious to thermal, physical, or chemical attack. Because of their hardening mechanism, there are varying amounts of dimensional change from class to class—that is, epoxies shrink very little, whereas ureas shrink considerably more. As such, they may be good gap fillers, either in their raw state or when modified with bulking agents.

Despite these qualities, the use of these adhesives in conservation is discouraged. By their very nature as cross-linking polymers, they are intractable and, therefore, not easily reversible.

Selection and Use of Adhesives in Wood Conservation

The most widely used adhesives at the Smithsonian Institution's Conservation Analytical Laboratory are hot and cold hide glues; there is only minor use of synthetic resin emulsions or solvent-borne adhesives. Cross-linking and multipart adhesives are almost never used as replacement adhesives when joint failure is treated.

Knowledge of an object's use and of the structural stresses that will be placed on the object during that use is particularly important when the choice of an adhesive treatment is made. A panel painting on a display easel will experience different stresses from those of a painting that is hanging, and the grain direction of a panel (and therefore its natural potential for either strength or damage) could affect its exhibition or storage orientation. In addition, the object may serve its function indefinitely in controlled circumstances, but only briefly under adverse environmental conditions. It is against this backdrop that an assessment of the object's condition must take place.

Treating wood fractures

Because this article is especially pertinent to wood panels, extremely rare cross-grain breaks will not be discussed. Instead, the focus will be on breaks that are essentially along the grain, or longitudinal with respect to the wood orientation of the panel.

Simple fractures

A simple fracture, whether partial or complete, requires only the introduction of an appropriate adhesive, alignment, and modest compression to complete the reassembly. To speak of an "appropriate" adhesive, however, is to be intentionally ambiguous, as there is a variety of possibilities. Selection depends on such factors as the stresses the object must withstand and the sensitivity of any decorative surfaces (no small consideration when dealing with polychrome panels).

A partial fracture of an object that is still in one piece (sometimes tenuously) does not always leave easy access to the gluing area. The glue must be applied either by allowing it to flow into the void under gravity or capillary action or by forcing it in under pressure by use of a hydraulic device, such as a syringe.

A complete fracture presents immediately accessible gluing surfaces, and adhesive can be applied directly with a brush, spatula, or other appropriate tool.

For both complete and partial simple fractures, the conclusion of the gluing process is to align the parts to be unified and to apply only enough restraint to hold them in place until the glue dries.

Complex fractures

Complex fractures are particularly challenging when the gluing surfaces are no longer adequate for the reassembly of the artifact, either because the panel is distorted, leaving a void in the alignment, or because the gluing surface itself is damaged by displacement or splintering of the wood fibers. As with a damaged gluing surface, decisions must be reached as to how vigorously the conservator is to intrude in order to make the artifact whole. These decisions must, by nature, be ad hoc, but there are some general guidelines for treatment strategies.

The existence of substrate voids, either in the fracture region as a whole or at the glue line in particular, may contribute to the overall structural instability of the object. (Whether or not the voids contribute to further deterioration depends on numerous construction, usage, and environmental factors outside the scope of this article.) The degree of instability, along with the anticipated future circumstances of the artifact, usually determines whether the voids are to be filled or left empty.

In the case of panel paintings, the fill must be made to fit the void exactly. This can be accomplished by either cutting a wood piece to fit the void precisely, casting flexible thermoset material into the void, filling the void with an inflexible thermoset material, or using a combination of these methods. Unless the fill is a tight wood-to-wood system, the gluing surface should be isolated from the fill with an easily reversible barrier film, such as animal glue or synthetic resin solution. The author has found the use of hide glue to be the most convenient and utilitarian material for this purpose.

Treating degraded or failed adhesives

Reactivation of adhesives

Although it is the least intrusive intervention, reactivation unfortunately is usually among the least successful. Because it involves the use of solvents or heat, reactivation is limited to cradles or other backing supports of panel paintings and is not suitable for the panels themselves. By definition this technique can be applied only to adhesive materials that are thermoplastic and not so degraded as to prevent any useful re-formation of an adhering film. Even when successful, this approach rarely yields a strong bond, and the object may be incapable of fulfilling its normal use.

Reactivation is most commonly applied to aged hide glue, but it can also be applied to synthetic solvent-based adhesives, which, as mentioned above, are frequently present in artifacts as part of a previous attempt to rectify damage. Reactivation is usually done when other methods are not possible, but the resulting bond may not be strong enough to allow normal use of the object. With respect to panel paintings, there is also the very real possibility of damaging the decorative surface of the object; solvents that dissolve polymeric adhesives will also act as paint removers for many coatings.

Introduction of a new adhesive

A more intrusive repair method, but one with a greater chance of success than reactivation, involves adding new adhesive to the glue line to augment failing adhesives. The usual objective is to fill any voids completely, thereby providing the necessary degree of strength and the greatest possible stability and durability. The primary constraint on this technique is that the newly introduced adhesive must be compatible with and bond to the existing adhesive.

In general, this method of stabilizing the structure is used only for adhesives that are readily soluble in the same solvent and thus can meld together to form a cohesive bond. Hide glue is most commonly used for this type of repair. Water-based emulsion glues can be added to existing hide glues, as they will bond reasonably well. However, adding a glue such as PVA emulsion, with different mechanical properties that would make it react differently to environmental changes, can lead to failure of the glue line. This consequence, as well as concern over the long-term stability of PVA emulsion, discourages its use in wood conservation.

There is growing interest in synthetic hot-melt adhesives for this type of treatment. Although further investigation of hot-melt adhesives is needed, there is no theoretical reason why this treatment option should not be developed.

Replacing failed adhesives

The option of completely removing the aged adhesive materials is available, but it should be undertaken only in cases in which the object can be completely disassembled and the conservator has access to all gluing surfaces. For panel paintings, this treatment would be limited to backing supports. There is frequently a need to remove all of the existing glue because of the number of factors that contribute to adhesive failure, from environmental fluctuations to inept previous repairs with inappropriate adhesives. The continued presence of a failed glue on an object contributes to its accelerated deterioration.

Any adhesive material that can easily be removed mechanically with a tool without damage to the substrate is treated first. If mechanical removal cannot be done easily and cleanly, solvents are added to the procedure. The adhesive will swell and/or soften so it can be removed with wooden scrapers or cotton swabs.

Conclusion

The nature of the adhesive materials used on artifacts often reveals vital information about their historical/material technology that can provide useful clues and direction to the caretakers of the objects. The wise conservator will base conservation treatments requiring adhesive processes on a sound understanding of these processes.

Note

1 Most sources discussing the technology of natural resins refer to their widespread utility as coatings, sealants, and adhesives. See Koob 1984 and Mantell 1942.

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Consolidation of Wooden Panels

Arno P. Schniewind

Wooden panels for paintings were traditionally made of solid wood and consisted of either a single board or, for larger panels, a series of boards edge-glued to form the required size. Today a variety of wood-based panel materials are available as painting supports, including plywood, fiberboard, hardboard, and particleboard. Among these types, plywood (in the sense of wood with decorative face veneers) has been known since ancient times, but machine-made commercial plywood is of more recent origin. It appears to have found use as a support for paintings in the latter half of the nineteenth century (Muller 1992). The other wood-based materials are largely developments of the twentieth century, with particleboard coming into general use only after World War II.

In the general sense, the term *consolidation* refers to merging or joining separate parts or to making something strong and stable or to making it solid and compact. As used by conservators, the term refers to remedial treatments of materials that have lost cohesion as a result of deterioration, in order to stabilize an object and make it safe for its intended use (Wermuth 1990). It is thereby understood that a material to be consolidated has some degree of porosity, so that another substance can be introduced into the pore space to achieve a particular objective, such as strengthening of deteriorated wood. Consolidation can therefore be thought of as a kind of internal gluing. It is no accident that the theme of the Tenth International Congress of the International Institute for Conservation was "Adhesives and Consolidants," as the difference between the consolidation of a porous material and the use of adhesives to join together something like the shards of a broken ceramic vessel is largely one of scale (Brommelle et al. 1984).

The basic objective of consolidation is to assure the stability and safety of an object. In addition, specific objectives will vary with the intended use. The most demanding of these is when consolidation is required to reestablish full functionality of an object. Usually this will be the case when the object serves a significant structural function, as, for instance, structural wood members in a building or the legs of a chair that people will sit on. A less demanding level would be when stabilization is required through all or most of the interior of an object. Finally, in some cases, only a consolidation of surface layers may be required to prevent damage by abrasion. Objects in museum collections would rarely require reestablishment of full functionality but must be able to withstand some handling and perhaps the rigors of shipping.

Consolidation is a major intervention that is not to be undertaken lightly. In particular cases of advanced deterioration, however, it may become a necessary treatment. Once the necessity for consolidation is determined, a number of decisions must be made regarding materials and methodology. These decisions include choice of a consolidant, solvent (and level of solution concentration), and suitable method of application. Much will depend on the nature of the object to be treated, the type and condition of the material, and the functional requirements of the object. Usually structural function, as well as visual aspects, will be addressed. The present discussion will be directed to a comprehensive examination of various aspects of the consolidation of deteriorated wood, proceeding from consideration of the general to the more specific problems that might be encountered in the consolidation of wooden panels that support paintings. Hereafter, all references to wooden panels refer to painting supports. No attempt will be made to consider the consolidation of waterlogged wood, because that process presents problems and requires approaches not applicable to panel paintings.

Permeability of Wood

Consolidation of deteriorated wood entails the introduction of another substance into its porous structure, a process requiring that the substance be in fluid—liquid or gaseous—form. The ease with which a fluid can be introduced is governed by the permeability of the wood. The transport (movement) of fluids through wood can be represented by Darcy's law (Siau 1984):

$$\text{flux} = \text{permeability} * \text{gradient} \tag{1a}$$

where flux is the volume of flow per unit time and unit area perpendicular to the flow direction, and gradient is the change in pressure over the flow path. Permeability depends both on the nature of the material and on the viscosity of the fluid that flows through it. Hence we get:

$$Q/A = (K/\eta)\,(\Delta P/L) \tag{1b}$$

where: Q = rate of flow (volume per unit time); A = cross section perpendicular to the flow path (area); K = specific material permeability (volume per unit length); η = viscosity of the fluid (force per unit area times time); ΔP = pressure differential across the flow path (force per unit area); and L = length of flow path (length).

Inspection of Equation 1b reveals that fluid viscosity and pressure differential are the only variables available for manipulation, because for a given object, the cross-sectional area, the specific material permeability, and the flow path are fixed. A high viscosity results in a low rate of flow, while a high pressure differential produces a high rate of flow.

Alternatively, flow through wood can be modeled as capillary flow, in which case Poiseuille's law applies (Siau 1984). This is given by:

$$Q = (N\pi r^4 \Delta P)/(8\eta L) \tag{2}$$

where: N = number of capillaries (no.); r = capillary radius (length); and all other variables are as previously defined. Here radius and number of capillaries take the place of the cross-sectional area and specific material permeability. It should be pointed out, however, that while the term $N\pi r^2$ defines an area, this is the area of the capillary openings and not the same as the cross-sectional area in Equation 1b. Again, a high flow rate can be achieved by either a low viscosity or a high pressure differential and, in this sense, Poiseuille's law is the same as Darcy's law.

Equations 1a, 1b, and 2 are for steady state flow, where the fluid enters on one surface and exits on an opposite surface. In consolidation treatments, a more realistic model is given by unsteady state conditions, where the fluid enters from opposing surfaces. For a parallel-sided body, the fractional volumetric retention of fluid—that is to say, the volume of fluid retained in the body expressed as a fraction of its total volume—is given by (Siau 1984):

$$F_{VL} = 2/L\,[(2K\Delta Pt)/(V_a\eta)]^{1/2} \tag{3}$$

where: F_{VL} = fractional volumetric retention (volume per volume); L = distance between the opposing surfaces (length); K = specific permeability of wood (volume per length); t = elapsed time from beginning of treatment (time); V_a = porosity of the wood (pore volume per total volume); and other values are as previously defined.

Examination of Equation 3 shows that here also, all variables except viscosity and pressure differential are fixed for a given object and that high retention requires high pressure differential or low viscosity.

Pressure impregnation is ordinarily not a realistic choice in conservation work, but vacuum impregnation is effective and relatively easy to do (Schaffer 1974; Barclay 1981; Payton 1984; Simpson, Spirydowicz, and Dorge 1992). For any other application methods, one must simply substitute an alternate driving force for pressure differential (i.e., gravitational forces or the surface tension involved in wetting and capillary action). Thus, the viscosity of the fluid chosen for consolidation is the key factor in successful consolidation treatments (Schaffer 1971).

The permeability of sound wood is an extremely variable property. Permeability may vary from one species to another by as much as a factor of 1 million. Longitudinal permeability is greater than transverse (radial or tangential) permeability, with ratios varying from 500 to 80,000 in softwoods and from 30,000 to over 100 million in hardwoods (Siau 1984). Biological deterioration can cause dramatic increases in permeability, particularly if the organisms destroy the pit membranes (Ellwood and Ecklund 1959). Thus, the ease of treatment tends to increase with the degree of deterioration.

Criteria for Selection of Consolidants

A number of authors have discussed desirable characteristics of consolidants (Grattan 1980; Unger 1988; Rosenqvist 1963; Werner 1977). Grattan lists as many as eleven "ideal characteristics" (Grattan 1980). The major concerns of conservators are included in the following list of requirements of consolidants:

1. Long-term stability is necessary so that the consolidant does not deteriorate at a faster rate than the object itself.
2. The treatment should not change the appearance of the object. Undesirable changes include darkening, color changes, and glossy surface films where no gloss was extant or intended.

3. No internal stresses should be imparted to the object by shrinkage of the consolidant upon solidification. In extreme cases, such stresses could cause internal ruptures and distortions of the object.
4. The consolidant should be compatible with other materials, such as paint, that are either already present or might be added later during additional treatments.
5. The treatment should be reversible. Grattan felt that reversibility was necessary at least in the short term, if for no other reason than to allow correction of any mishaps that might occur during treatment (Grattan 1980).
6. The consolidant should be an effective strengthener.
7. The treatment should be capable of good penetration and result in ample deposition of consolidant.

The order of this list is somewhat arbitrary, because priorities vary with each case. For panel paintings, compatibility with other materials is of major importance because any interference with the ground or the paint layers will not be tolerated. It should also be noted that even though some of the first five items are couched in positive terms, they all refer to characteristics that consolidants should not have. They should not deteriorate, change appearance, cause stresses, interfere with associated materials, or be permanently fixed. Only the last two refer to positive effects, and in a sense, the sixth item implies the seventh. Thus, this review of the requirements of consolidants stresses the importance of making sure that a consolidation treatment will not harm the object.

Types of Consolidants

Types of consolidants may be divided into two categories: natural and synthetic materials. Comprehensive and detailed overviews of various types of consolidants for deteriorated wood are given in the literature (Unger and Unger 1987; Unger 1988).

Natural materials

Natural materials include hide glues, waxes, resins, and cellulose derivatives. Except for cellulose derivatives, which did not become available until the end of the nineteenth century, natural materials are also the traditionally used materials.

Hide glues have several significant disadvantages as consolidants: they do not penetrate well into the wood structure; they will shrink and swell in response to humidity fluctuations; they are not moisture resistant; and they will become brittle over time.

Waxes, specifically beeswax and paraffin, have been used as consolidants in the past either alone or as wax-resin mixtures. Using wax is a disadvantage because treated objects look greasy, attract dust, and darken with age. Furthermore, the strengthening that can be achieved is minimal. Unger refers to several examples of wooden panels treated with wax or wax-resin mixtures. Once applied, the wax is nearly impossible to remove entirely; therefore, residues may interfere with later treatments (Unger 1988).

Natural resins such as damar, shellac, and rosin have been used extensively in the past. However, these resins produce only moderate strengthening, and they embrittle with age. Unger cites a large-scale project in Austria, in which an altar was consolidated in the 1950s using 1500 l of shellac in ethanol (Unger 1988).

Drying oils, especially linseed oil, have also been used as consolidants in the past, but they provide very little effective strengthening.

Cellulose derivatives (acetate or nitrate) did find use as consolidants during the first half of the twentieth century, but today their application has virtually ceased. It is difficult to achieve much penetration with the cellulose derivatives, and the materials discolor and embrittle with age.

Natural materials are thus seen to have significant disadvantages. Therefore, further discussion focuses primarily on synthetic polymers.

Synthetic polymers

Synthetic polymers can be divided into thermosetting and thermoplastic types. This division is important in conservation, because thermosetting resins that might find use in consolidation generally are not soluble in organic solvents. Therefore, their use results in irreversible treatments. Thermoplastic resins are generally soluble in organic solvents, although they can become cross-linked, which leads to a loss of solubility (Ciabach 1983; Bockhoff et al. 1984).

Thermosetting resins

One class of thermosetting resins that might be considered for use as consolidants consists of the formaldehyde resins: phenol, resorcinol, urea, and melamine. These are widely used as adhesives in the production of wood-based materials, because they are excellent adhesives for wood. Phenolic and resorcinol resins are also waterproof and very resistant to weathering. Unger cites some past uses of these resins in conservation; however, there appears to be little, if any, such use at present (Unger 1988). A particular drawback of these resin systems is poor penetration, and all but the melamine formaldehyde resins either are initially dark or darken with age.

Epoxy resins have found wide application in the rehabilitation and repair of wood and concrete structures, and they are successfully used in stone consolidation because of their excellent durability, adhesion, and strength (Phillips and Selwyn 1978; Stumes 1979; Selwitz 1992). Unlike the formaldehyde resins, which shrink upon hardening, epoxy resins in their neat formulation do not change volume as they harden; consequently, shrinkage stresses are avoided. However, the neat resins have relatively high viscosity and therefore penetrate poorly. Penetration can be improved by the addition of solvents to reduce viscosity. Unger gives a number of examples where epoxy resins have been used in wood conservation projects, including some treatments of wooden panels. Their main application lies in strengthening structural members in wooden buildings or in strengthening museum objects that are exposed to the weather. According to Unger, epoxy resins are suitable for consolidation of wooden panels only if the wood is very severely deteriorated, because application into wood that is only moderately deteriorated results in insufficient penetration (Unger 1988). This may not apply if the small-molecule epoxies advocated by Munnikendam are used, however, because in their neat formulation they have about the same viscosity as 15% Acryloid B72 in acetone (Munnikendam 1973).

Thermoplastic resins

Thermoplastic resin consolidants can be introduced into wood as monomers or prepolymers and polymerized in situ, using either irradiation or a combination of heat and a catalyst to initiate the polymerization reaction. Commercial production of wood-polymer composites uses vinyl-type monomers such as styrene, methyl methacrylate, vinyl acetate, or acrylonitrile, but methyl methacrylate is considered to be best suited for industrial products (Meyer 1989). Unless cross-linking agents were introduced, the resin may still be soluble after polymerization, but in practical terms very little chance of removal remains. Unger and coworkers found that surface films and crusts remaining after they treated old pistol grips with mixtures of methyl methacrylate, styrene, and polyester could only be removed with considerable difficulty (Unger, Reichelt, and Nissel 1981). Schaudy has made extensive studies of a wide variety of consolidants that can be cured by irradiation. Some of these findings have been summarized recently: only certain resins tested were found suitable, but many types of objects, including polychrome wood, have been treated successfully (Schaudy 1990). The advantage of curing in situ lies in the low viscosity of monomers or prepolymers, which assures good penetration and good resulting strength. However, it is not likely to be the method of choice for use on panel paintings because of difficulties in ensuring that the ground and paint layers will remain unaffected by the treatment.

Alternatively, thermoplastic polymers can be introduced into deteriorated wood in solution form. Commonly used polymers for this purpose are polyvinyl acetate (PVA), polyvinyl butyral, acrylics, and soluble nylon (Grattan 1980; Unger 1988). Of these, soluble nylon is no longer used because it has poor durability and loses its solubility very quickly due to cross-linking (Bockhoff et al. 1984). The advantages of the other three types of resins are that they are reversible at least in principle; they can be applied by a variety of methods; and, in the case of PVA and acrylics, they have a record of stability extending over a period of more than sixty years. Disadvantages are that some solvents may cause the wood to swell during treatment, and that the strengthening effect is not as great as that which can be achieved with epoxy resins and other materials. With regard to PVA and acrylics, of particular interest is their use in picture varnishes: should these resins be used as consolidants for wooden supports of paintings varnished with such products, a degree of compatibility could be assured.

Application of Consolidants

Consolidants must be in either gaseous or liquid form if they are to be applied to deteriorated wood. There is one method of applying gas-phase consolidant that uses Union Carbide Corporation's Parylene polymers (Humphrey 1986). However, this process does not appear to penetrate sufficiently for effective wood consolidation, and the consequent thin films achieved would provide very little strengthening. In liquid form the consolidants may be in the molten state (e.g., waxes); they may be liquid monomers that are then polymerized in situ (e.g., methyl methacrylate); or they may be thermoplastic polymers in solution (e.g., PVA in acetone).

Choice of solvent and concentration for consolidant solutions

Since each synthetic resin has its own particular requirements, the choice of solvent is immediately limited to those that can provide solutions of compatible concentration and viscosity for the chosen resin. In wood consolidation, the choice between polar and nonpolar solvents is significant. Although polar solvents have an affinity for wood, they tend to penetrate poorly compared to nonpolar solvents, because polar molecules may be adsorbed on the internal wood surfaces, and such adsorption would reduce their mobility (Nicholas 1972).

As an organic solvent's degree of polarity increases, so does its tendency to swell wood. For example, among commonly used solvents, the virtually nonpolar toluene swells wood a mere 1.6% as compared to the swelling by water. Meanwhile, the polar acetone, ethanol, and methanol produce swellings of 63%, 83%, and 95%, respectively (Stamm and Harris 1953). In deteriorated Douglas-fir samples, vacuum impregnation with 15% solutions (weight basis) of consolidants produced values of swelling in the tangential direction measured immediately after treatment as shown in Table 1. When the nonpolar toluene was the solvent, swelling was less than 0.1% with two different resins, whereas Butvar B98 in methanol produced a swelling of 3.31%. This swelling was not permanent, though, and after four weeks most of the swelling had been recovered (Schniewind 1990b). With panel paintings, however, even temporary swelling could prove objectionable, as this might lead to undesirable stresses in the paint layers.

Table 1 Swelling of wood samples immediately after consolidation treatment

Solvent and consolidant	Swelling (%)
Acryloid B72 in toluene	0.06
AYAT in toluene	0.07
Acryloid B72 in acetone	1.03
AYAT in acetone	2.17
Butvar B98 in methanol	3.31

Another point to consider is that solvents with low boiling points are usually preferred over those with high ones, so that residual vapors persisting after treatment can be avoided. Residual solvents have other effects that will be discussed later.

When solution concentrations are chosen, it is necessary to balance the desire for good penetration—which can be achieved by keeping the concentration and hence the viscosity low—against the need to obtain a reasonable level of resin loading (the resin content after treatment). Given equal penetration, loading can be increased by increasing consolidant concentration. Thus, low concentration tends to yield good penetration but poor loading, whereas high concentration conversely results in poor penetration but good loading. Resin loading is important because the effectiveness of consolidation treatments largely depends on the amount of resin that can be added. The maximum possible loading can be calculated from the porosity of the wood. This is given by (Kellogg 1989):

$$V = 1 - \rho_1 (1/\rho_w + M_b/\rho_b + M_f/\rho_f) \tag{4}$$

where: V = fractional pore volume; ρ_1 = relative density (specific gravity) of (porous) wood, based on oven-dry weight and current moisture content; ρ_w = relative density of cell-wall substance; M_b = content of bound water; ρ_b = relative density of bound (adsorbed) water; M_f = content of free water; and ρ_f = relative density of free water.

For instance, let us take wood with a relative density of 0.5 and a total moisture content of 12% and treat this to saturation (i.e., filling all pore volume completely) with a solution that contains 10% Butvar B98 by volume. With a relative density of cell-wall substance of 1.5 and a relative density of the bound water of 1.014 (note that 12% is less than the fiber saturation point in wood so that no free water will be present), the fractional pore volume can be calculated as: $V = 1 - 0.5\ (1/1.5 + 0.12/1.014) = 0.61$ (Kellogg 1989). Butvar B98 has a relative density of 1.1. Of the total pore volume, 10%, or 0.061, is occupied by resin. Since a relative density of 1.1 corresponds to a density of 1100 kg m^{-3}, this converts to 67 kg m^{-3}; and when this is added to the wood density of 500 kg m^{-3}, it represents an increase, or resin loading, of 13.4%. The relative density of 0.5 corresponds to the high end of the range for typical softwoods in their original state. As the wood deteriorates, the relative density decreases and the porosity increases, making higher loading possible. In impregnation of wood with monomers, with subsequent curing in situ, much higher loading is possible—even when the polymer shrinkage during curing and the loss of monomer due to evaporation are taken into account (Simunkovà, Smejkalovà, and Zelinger 1983; Schneider 1994).

Methods of application

The most simple and straightforward way to apply consolidant is by brushing. In most cases it is quite difficult to get substantial penetration by brushing, but an adequate treatment can result if only the surface layers need to be strengthened. For catalyzed systems (i.e., thermosetting resins or resins polymerized in situ), brushing is probably the least effective method because the treatment is limited to a single application. Consolidant solutions, however, offer a somewhat better prospect, since it is possible to make more than one application. Grattan found that better results could be obtained by applying many coats of consolidant solution of low resin concentration, whereas solutions of high concentration can lead to the early development of an objectionable gloss on the artifact surface (Grattan 1980). Barclay was able to use a brush treatment of 5% solution of Butvar B98 in ethanol on portions of an English fire engine with good results (Barclay 1981).

To improve on the penetration achieved by brushing, some form of treatment that keeps the object in contact with consolidant solution over a period of time without allowing any intermediate drying can be very effective. This procedure can take the form of soaking in consolidant solution, as with two canoes treated with PVA in toluene in Japan (Chemical Section and Section for Repairing Technique 1968). However, considerations of cost, safety, and eventual disposal problems may speak against the use of the large quantities of solution that would be required for large objects. The alternative approach is to use a continuous or intermittent recirculating spray system within an enclosed space. A California Native American dugout canoe was treated in this manner. The treatment used a 13% solution (weight basis) of AYAT, a PVA, in methanol within a temporary enclosure, and achieved complete penetration of the wood (Schniewind and Kronkright 1984). A somewhat different approach was used by Nakhla (1986): consolidant solution was applied in drops onto the objects being treated. As long as the rate of application is consistent enough to keep the object wet with solution, this can also be a very effective method. Consolidant may also be injected selectively (Wermuth 1990).

The most effective method of achieving maximum penetration is to use vacuum impregnation, which can be a practical method, except in the case of very large objects (Schaffer 1974). The easiest method is to draw a vacuum while the object is submerged in consolidant solution within the vacuum chamber; the vacuum is continued until most of the air has been drawn from the porous wood structure. The vacuum is then released, causing atmospheric pressure to push the consolidant solution into the wood. For maximum results, the vacuum should be drawn first and the consolidant solution subsequently introduced to cover the object while under vacuum, so that the solution does not impede the removal of air from within the wood. However, this approach would require elaborate equipment, which would probably not be justified in most cases. Some parts of the fire engine previously mentioned were treated by vacuum impregnation, using a solution of 20% Butvar B90 in ethanol. The relatively high concentration was chosen to maximize loading, and the vacuum impregnation method was relied upon to achieve sufficient penetration (Barclay 1981).

While most of the examples given above are of consolidation treatments with soluble resins, the methods of application described can be executed with any type of liquid used for consolidation. For panel paintings it is difficult to visualize much other than brush treatments from the back. A possible exception would be soaking the panel face up in a shallow pan containing a small amount of consolidant. In any case, care must be taken that the consolidant does not reach either the ground or the paint layers—or at least, if it should reach the ground, that it does not change the ground's characteristics.

When solvents are used to introduce consolidants into deteriorated wood, there is potential concern that during solvent removal, evaporation from the surface will result in reverse migration of consolidant from the interior toward the object's surface (Payton 1984). When solvents are used solely to improve penetration of thermosetting resins, reverse migration can be reduced or eliminated by the prevention of solvent evaporation until the resin has been cured and fixed within the object (Selwitz 1992). Migration of water-soluble wood extractives to the wood surface can be observed in the course of normal lumber drying (Anderson et al. 1960). Reverse migration of soluble resins during solvent removal in stone consolidation can be mitigated by reduction of the rate of drying (Domaslowski 1988). Terziev and coworkers found that water-soluble sugars present in the sap of freshly cut wood would undergo significant redistribution during drying and that much more sugar migrates toward the surface during fast, as compared to slow, drying schedules (Terziev, Boutelje, and Söderström 1993). Samples of deteriorated Douglas-fir treated with Acryloid B72, Butvar B98, or Butvar B90 had lower bending strengths when dried very slowly, as compared to samples dried more rapidly in the open air (Wang and Schniewind 1985). The samples of B98 and B72 dried in the open air were examined by scanning electron microscopy to determine consolidant distribution. The results showed that the consolidant was more heavily concentrated near the surface than in the core. Since the samples had originally been completely saturated with consolidant solution, this was definite evidence of reverse migration (Schniewind and Eastman 1994). While the slowly dried samples were not examined for consolidant distribution, the observation of lower bending strength is consistent with less reverse migration, due to the slow rate of drying. The strength of beams depends more on the upper and lower surface layers than on the core; therefore, a greater concentration of consolidant in the surface layers would tend to increase bending strength of the samples.

Consolidant Effectiveness

Among the seven criteria for selection of consolidants discussed above, the most important positive characteristic is that the consolidant serve as an effective strengthener. This characteristic depends on a number of factors, including the amount and distribution of the consolidant, as well as the properties of the solidified consolidant itself.

Properties of wood and consolidant composites

The addition of consolidant to deteriorated wood produces a composite with resultant properties that depend on the relative amounts and properties of both components involved. One method for predicting the mechanical properties of composites is the so-called rule of mixtures, which can be stated as follows for the modulus of elasticity (Siau et al. 1968):

$$E = E_w V_w + E_p V_p + E_a V_a \tag{5a}$$

where: E = modulus of elasticity of the composite; E_w, E_p, E_a = modulus of elasticity of wood substance, consolidant, and air, respectively; and V_w, V_p, V_a = volume fraction of wood substance, consolidant, and air, respectively.

If we remove the term for the consolidant from the right-hand side of Equation 5a, we get the modulus of elasticity of gross wood, E_g, as a composite of wood substance and air. Since the consolidant is simply contained in the air space of the porous wood, Equation 5a can therefore also be given as (Wang and Schniewind 1985):

$$E = E_p V_p + E_g \tag{5b}$$

This equation can also be used for estimating other mechanical properties of wood and consolidant composites. Wang and Schniewind used Equation 5b to estimate both strength and stiffness in bending of treated Douglas-fir samples, and they obtained reasonably good agreement with actual test results. However, estimates tended to be on the low side—the probable reason being a greater concentration of consolidant in the surface layers, which would tend to improve the bending strength of the composite more than a uniform distribution (Schniewind and Eastman 1994).

Since the volume fraction of consolidant, V_p, is one of the factors in Equation 5b, it follows that the strengthening effect of consolidation should be positively related to the amount of loading achieved. This is not only intuitively obvious but also shown to be true by experimental results for monomers polymerized in situ (Simunkovà, Smejkalovà, and Zelinger 1983) and for polymers introduced in solution (Wang and Schniewind 1985). The value of V_p in Equation 5b will always be less than 1. The contribution of the consolidant to the properties of the composite will therefore depend highly on the strength of the consolidant in relation to the strength of the wood. As an extreme example, a polymer that has 10% of the strength of normal wood, if impregnated to a volume fraction of 10%, would only increase the strength of the composite by 1% over that of the wood alone.

Conversely, the more severely deteriorated the wood, the greater the strengthening effect of a given consolidation treatment. This idea is illustrated in Figure 1, which shows improvement factors for different levels of deterioration (Schniewind 1990a). In this example the strength of the most severely deteriorated wood was increased by 47%, while that of the least damaged wood improved by only 10%.

Epoxy resins can be formulated with excellent strength properties, which is an important justification for their potential application in the repair and consolidation of engineered structures. Accordingly, epoxy resins will result in probably the best possible strengthening in the consolidation of deteriorated wood if their use can be justified. Similarly, vinyl monomers polymerized in situ in normal wood at a loading of approximately 50% produced increases in bending strength on the order of 70–80% (Siau et al. 1968) and from 100% to more than 600% increases in compression strength perpendicular to grain (Meyer 1989). Consistent with Equation 5b, the greater increases in compression strength perpendicular to grain are possible because wood is weaker perpendicular to grain than parallel to grain, and strength parallel to grain is the determining factor in bending strength.

The strengthening effect of soluble thermoplastic polymers tends to be significantly less, because it is rarely possible to achieve levels of loading as high as 50% and because of the lower strength of the resins themselves. Physical data for several commonly used soluble resin consolidants and their improvement factors are shown in Table 2. Deteriorated Douglas-fir was used, with the loading between 20% and 23% (Schniewind and Kronkright 1984; Wang and Schniewind 1985). Butvar B98 is seen to give the greatest strengthening, followed by Acryloid B72. All but the three PVA resins with the lowest molecular weights gave statistically significant levels of improvement. Considering that the tensile strength of normal Douglas-fir is on the order of 125 MPa, it can be seen that the tensile strengths of all resins for which data are available are less than that of the wood. This is particularly true for the PVA resins, which also have glass-transition temperatures, T_g, either below or not much above room temperature—bringing them close to or into a rubbery, rather than glassy, rigid state. Of course, in some circumstances such flexibility may be

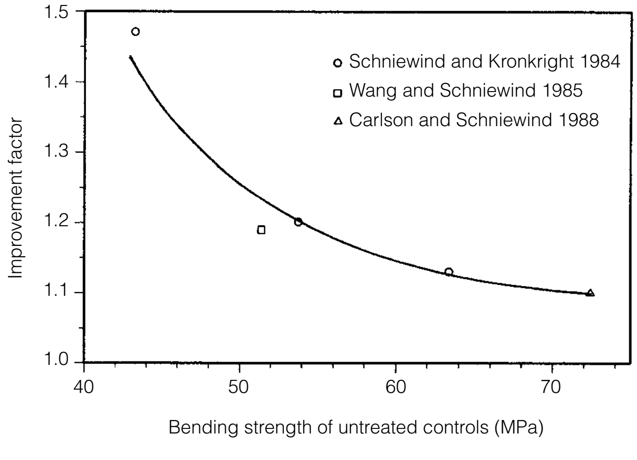

Figure 1

Improvement factor: ratio of bending-strength values of wood treated with Butvar B98 to bending-strength values of untreated wood, for deteriorated Douglas-fir at various levels of residual bending strength (degrees of deterioration).

Table 2 Properties of resins and their strengthening capability, or improvement factor, calculated as the ratio of bending strength of treated deteriorated Douglas-fir samples to that of untreated controls. The asterisk denotes a value that is not practical to measure.

Resin	Molecular weight	Tensile strength (MPa)	T_g (°C)	Improvement factor	Reference
Butvar B90	45,000	46	68	1.14	Wang and Schniewind 1985
Butvar B98	34,000	46	68	1.19	Wang and Schniewind 1985
Butvar B98	34,000	46	68	1.20	Schniewind and Kronkright 1984
Acryloid B72	—	—	40	1.16	Schniewind and Kronkright 1984
AYAT	167,000	29	28	1.13	Schniewind and Kronkright 1984
AYAF	113,000	18	24	1.10	Schniewind and Kronkright 1984
AYAA	83,000	10	21	1.03	Schniewind and Kronkright 1984
AYAC	12,800	*	16	1.11	Schniewind and Kronkright 1984

desirable, but this characteristic also means that little strength can be added to the much stiffer material that is being consolidated.

Influence of solvents used for thermoplastic resins

The choice of solvents for thermoplastic resins can influence the ease of penetration, either by the degree of solvent polarity or by the resulting solution viscosity. The property of a given polymer deposited from solution may depend on the dynamic quality of the solvent used. Hansen and coworkers found significantly different mechanical properties of films of AYAT cast from acetone and from toluene, with toluene giving the lower values (Hansen et al. 1991). Wang and Schniewind found evidence that the use of polar rather than nonpolar solvents tended to result in somewhat greater levels of strengthening (Wang and Schniewind 1985). The distribution of consolidant, however, was not significantly affected by solvent polarity (Schniewind and Eastman 1994).

Solvent polarity was also found to be an important factor in the study of the incidental adhesive qualities of soluble resin consolidants (Sakuno and Schniewind 1990). It should be noted that adhesives and consolidants differ fundamentally in their formulation, regardless of the similarities discussed. Consolidants are formulated at low viscosity to achieve maximum penetration; adhesives for a porous material like wood must be formulated to have relatively high viscosity in order to limit penetration, since most of the adhesive should remain on the surfaces to be joined. Thus Koob used Acryloid B72 in acetone as an adhesive at a concentration of 50% (weight basis), as compared to the 10–15% concentration used for consolidation (Koob 1986). Sakuno and Schniewind used 15% solutions (weight basis) of AYAT, Acryloid B72, and Butvar B98, each in two different solvents, to study the incidental adhesive qualities of consolidant solutions (Sakuno and Schniewind 1990). These incidental adhesive qualities of consolidants relate to their ability to reattach loose fragments in the process of consolidation treatment. The results are summarized in Figure 2. Not unexpectedly, none of the consolidant solutions performed as well as the commonly used PVA “white glue” adhesive, the explanation for which is based

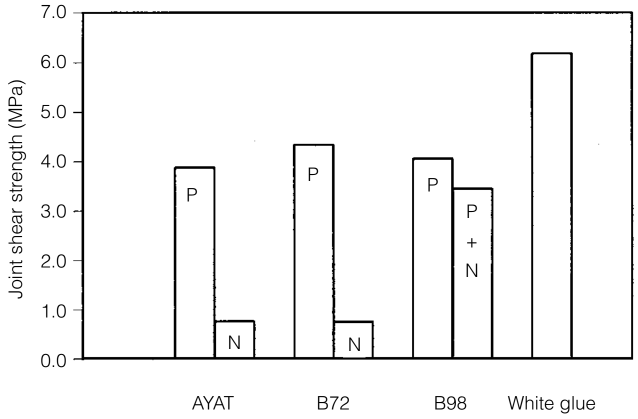

Figure 2
Static shear strength values for adhesive joints in deteriorated Douglas-fir made with AYAT, Acryloid B72, Butvar B98, and PVA emulsion white glue. P = polar solvent; N = nonpolar solvent.

on the relatively low concentration used. When polar solvents were used—acetone for Acryloid B72, and ethanol for AYAT and B98—all three resins performed about the same. For B98 no pure nonpolar solvent could be located, but the adhesive qualities of Acryloid B72 and AYAT in the nonpolar toluene were only a fraction of what was found with polar solvents.

Solvent volatility is another consideration. Solvents may be retained for a period, as shown in Table 3, for cast films of Acryloid B72 and Butvar B98. Missing values of T_g indicate values too low to measure. The more volatile solvents with low boiling points, such as acetone, can be removed more readily following treatment. This relative ease of removal reduces problems with objectionable residual vapors as well as with solvents retained by the consolidant resin. Retained solvents will lower the T_g of the resin and tend to make it less effective (Carlson and Schniewind 1990), but this result can be minimized by the use of solvents with low boiling points. However, less volatile solvents may prove superior in cases when consolidant is applied by brushing, since they would allow more time for deeper penetration.

Schniewind examined the effect of aging on consolidated wood samples (Schniewind 1990b). Bending tests made two weeks, one year, and three and a half years after treatment of deteriorated wood with B98 in ethanol or a mixture of ethanol and toluene, and Acryloid B72 in acetone or toluene, showed no overall aging effect. The sole exception was

Table 3 Glass-transition temperatures (T_g) and retained-solvent concentrations of cast films of Acryloid B72 and Butvar B98. The asterisk denotes the azeotrope boiling point of toluene-ethanol-water.

	Solvent		Drying condition					
			1 day, 20 °C		30 days, 20 °C		50 days, 20 °C	
Polymer	Type	Boiling point (°C)	T_g (°C)	Residual solvent (%)	T_g (°C)	Residual solvent (%)	T_g (°C)	Residual solvent (%)
B72	Acetone	56	—	5.8	39	0.3	40	0.0
B72	Ethyl acetate	77	—	6.3	—	2.2	40	0.2
B98	Methanol	65	—	19.7	54	3.2	75	0.3
B98	Ethanol-toluene	74*	—	12.3	49	4.8	66	1.5

Acryloid B72 in toluene, where bending strength increased significantly between two weeks and one year, but not thereafter. This may well have been a case where retained solvent did reduce the short-term strengthening effect of the consolidant.

Consolidant effects on wood-moisture relations

Synthetic polymers introduced into wood can affect the amount and rate of water absorption, as well as the shrinking and swelling. The extent of this effect depends greatly on whether the polymer has entered into cell walls or is contained within the cell lumina. Major reductions in hygroscopicity can be obtained only by polymer occupying sorption sites within the cell wall, but depositions in the cell lumina will affect the rate of moisture sorption while reducing shrinking and swelling by as much as 20% (Schneider 1994). Although vinyl monomers do not swell wood and, therefore, do not enter the cell wall, Simunkovà and coworkers did obtain large reductions in hygroscopicity, water absorption, and swelling with methyl methacrylate polymerized in situ by irradiation (Simunkovà, Smejkalovà, and Zelinger 1983). Butyl methacrylate was less effective. The extent of the changes was proportional to polymer loading, which ranged up to about 60% polymer. By contrast, at a loading of 24%, it was not possible to detect an effect on hygroscopicity by a treatment of Acryloid B72 in acetone (Schniewind 1990b). This was not unexpected because a molecular weight of 3000 is about the maximum that can enter the cell wall—even in the presence of a swelling solvent like acetone—and Acryloid B72 is believed to have a significantly greater molecular weight. Another contributing factor may be that Acryloid B72 introduced in solution does not form a uniform film over the internal lumen surfaces but tends to concentrate heavily in some cells, leaving others with little or no resin in them (Schniewind and Eastman 1994).

Reversibility

Thermosetting synthetic polymers are not soluble in neutral organic solvents and cannot be softened by heat, making treatments with something like epoxy resins irreversible. In contrast, treatments with thermoplastic synthetic polymers are reversible, at least in principle. Grattan and Williams have questioned whether the reversing of consolidation treatments can ever actually be successfully executed—the argument being that if an object is frail enough to require consolidation, it will be too frail to withstand the stresses of having the consolidant extracted again (Grattan 1980; Williams 1988).

According to the principles of thermodynamics, all real processes are irreversible—even the simple act of placing a drop of water on a smooth but uncoated wood surface can result in minute irreversible changes (Schniewind 1987). Horie proposed four standards of reversibility, ranging from clearly irreversible—through a return either to original appearance or to a state that does not interfere with subsequent treatments—to a state where no trace of the original treatment remains (Horie 1983). Thus, in practical terms, it is useful to know if some or most (if not all) consolidant can be extracted again if necessary. Thermosetting resins are clearly irreversible and thus could never be removed if used as consolidants. Thermoplastic resins polymerized in situ are also not likely to be readily removed: Unger and coworkers found it difficult to remove even surface deposits of such resins from treated wooden objects after the polymerization reaction was complete (Unger, Reichelt, and Nissel 1981).

Thermoplastic consolidants introduced into wood in solution, however, do offer at least some degree of reversibility. Hatchfield and Koestler made a scanning electron microscopic study of ancient wood treated with Acryloid B72 in toluene and found that the consolidant could be largely extracted again but that some of the resin did remain (Hatchfield and Koestler 1987). Nakhla treated samples of cedar with Acryloid B72 in trichloroethylene, or polyvinyl butyral (Mowital B30H) in ethanol, and then extracted the consolidants by soaking in the same solvent used for treatment (Nakhla 1986). Although gravimetric measurements indicated that some consolidant remained in both cases, the Acryloid B72 treatment proved, on the whole, more reversible.

It must be emphasized, however, that solvents interact not only with the consolidant but also with the wood. Normal wood contains—in addition to its main constituents cellulose, hemicellulose, and lignin—an extremely varied group of compounds known as extractives. They are so named because they can be extracted with neutral organic solvents. Deteriorated wood may additionally contain degradation products that are also soluble. In the course of extracting consolidant, extractives and degradation products may also be removed (Schniewind 1987, 1988). Some solvents will also cause wood swelling, or they may extract some of the adsorbed water in the cell wall, and some may in turn be adsorbed on the internal wood surfaces.

Table 4 shows results of a systematic study of reversibility of wood consolidation with respect to extractive removal. Deteriorated Douglas-fir specimens (6 × 25 × 50 mm) were treated with 15% solutions (weight basis) of Butvar B98, AYAT, and Acryloid B72, each in two different solvents. After drying, the specimens were extracted by one of the following three methods: soxhlet extraction, soaking with agitation, or soaking only. Soxhlet extraction is the most effective extraction method available and should therefore indicate the limits of what is possible;

Table 4 Reversibility of consolidation treatments as indicated by residual resin content

			Residual resin (%)	
Polymer	Solvent	Extraction method	Measured	Corrected
Butvar B98	Methanol	Soxhlet	–0.3	0.8
	Toluene-ethanol	Soak and agitate	2.7	2.9
	Toluene-ethanol	Soak only	6.0	5.7
AYAT	Acetone	Soxhlet	–1.0	–0.3
	Toluene	Soxhlet	1.2	1.9
Acryloid B72	Toluene	Soxhlet	0.2	0.9
	Acetone	Soxhlet	–0.1	0.6
	Acetone	Soak and agitate	–0.3	0.4
	Acetone	Soak only	0.7	1.3

however, it is not a practical method except in the most unusual circumstances. Parallel samples were used to extract the wood only, to determine the amount of extractives that would presumably be removed along with the consolidant. Before and after each procedure, specimens were conditioned to constant moisture content in a controlled-environment room.

Table 4 shows residual resin content as the difference between original weight and weight after extraction, with correction for extractive removal considered both before and after. Negative values before correction occur if the true residual resin is less than the amount of extractives removed. Only one corrected value is negative, a result that may be due to imperfect matching with the samples for extractive-content determination. The data show that acetone and methanol were more effective generally in extracting consolidant than toluene or the ethanol-toluene mixture, and that AYAT and Acryloid B72 treatments were more reversible than the B98 treatment. The use of agitation was very effective, and for Acryloid B72 and acetone, it achieved results as good as, if not slightly better than, the results of the soxhlet extraction. The AYAT treatment in acetone proved the most reversible (Schniewind 1988). Thus, there is ample evidence that soluble resin consolidants can largely be extracted again, but that small amounts of resin are likely to remain.

Treatment of Wooden Panels

In the discussion thus far, it has been assumed that the consolidant used should not come into contact with either the paint or the ground layers. This constraint represents a severe limitation of accessibility for consolidation of a painted panel as compared to an unpainted wooden artifact, and this limitation would also make it practically impossible to treat a wooden panel that has a painted image on the reverse. Furthermore, soaking by total immersion or vacuum impregnation would not be possible unless an effective, temporary barrier could be created to isolate the paint layers from the consolidant. Still, consolidation of polychrome wooden artifacts by vacuum impregnation, particularly with monomers polymerized in situ, is not unknown, and some examples have been described by Schaffer (1974). For instance, methyl methacrylate monomer is quite volatile, and if care is taken, the monomer will evaporate from the surface layers before polymerization can take place, thus preventing the formation of any surface films. It may also be helpful if a temporary barrier coating can be applied to prevent potential problems. While such a total impregnation procedure should not be rejected outright, it must nevertheless be approached with the utmost caution.

The nature of the deterioration needs to be considered when the consolidation of wooden panels is approached. Deterioration rarely proceeds in a uniform fashion, so it is entirely possible that impregnation will be required only in localized areas. For example, fungal decay may well occur in scattered pockets. If deterioration was caused by insect attack, the nature of the boreholes (i.e., small or large, isolated or coalescent, clean or filled with frass) is an aspect that could have a bearing on treatment choices. In cases where there are large areas of loss, fillers for the larger voids may need to be considered. Wermuth advanced the concept of primary, secondary, and even tertiary consolidants in such a context (Wermuth 1990). There is no reason that this distinction could not apply to panel paintings in particular cases.

Special Problems with Wood-Based Panel Products

Wood-based panel products are often found among the supports for paintings of the twentieth century. In particular, these include fiberboard, hardboard, particleboard (also referred to as pressboard and chipboard), and plywood. All of these consist of wood elements and some type of binder or adhesive. A survey of wood-based composite materials used in twentieth-century furniture and the problems they represent have been discussed by Klim (1990).

Since the adhesives used may not be moisture resistant and because extreme moisture conditions can create significant internal stresses in the material, there is always the danger of failure of the adhesive bonds and subsequent disintegration of the panel material. Particleboard is particularly subject to recovery of the large deformations of the particles incurred during the original pressing process, when it is exposed to high relative humidity. This is known as springback, a condition that may result in thickness swelling of 20% or more, as well as in a disruption and roughening of the surface (Moslemi 1974). For this reason, particleboard has to be considered one of the most unstable painting supports. Prolonged conditions of high moisture may lead to complete disintegration; thus fungal decay is not likely to be a problem with particleboard, because it will disintegrate at moisture contents sufficient to support decay—before the decay itself can do much damage.

In plywood, moisture problems can lead to surface checking, which could easily disrupt thin paint layers (Minor 1993), or to delamination (Williams and Creager 1993). Neither of these problems lends itself to being solved by a bulk treatment such as impregnation. There are no readily apparent methods of dealing with surface checks, especially if they are numerous and the conditions leading to the checking are likely to be persistent (Minor 1993). Williams and Creager have outlined some approaches to dealing with delamination, ranging from local repairs to a partial transfer (i.e., discarding all but the face ply bearing the image and attaching it to an alternate support) (Williams and Creager 1993). The permeability of these new wood-based panel materials additionally differs from that of solid wood. In plywood, the lathe checks can serve as pathways for fluid transport along the grain within a ply, so that the wood is very permeable from its edges. Because of the adhesive layers, however, permeability through the thickness is quite low (O'Halloran 1989a). This factor could make plywood more difficult to treat if there is deterioration of biological origin that does not involve delamination. Particleboard and fiberboard are more permeable than solid wood because they contain interconnected void spaces (O'Halloran 1989b). As in the case of solid wood, whatever type of deterioration takes place will increase permeability, a factor that serves to facilitate treatment by impregnation.

Materials and Suppliers

Acryloid B72, Rohm and Haas Company, Independence Mall West, Philadelphia, PA 19105.

AYAT, Union Carbide Corporation, Old Ridgebury Road, Danbury, CT 06817.

Butvar B90 and B98, Monsanto Plastics and Resin Co., 800 N. Lindbergh Blvd., St. Louis, MO 63166.

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