# *Conservation Science Research: Activities, Needs, and Funding Opportunities*

**A Report to the National Science Foundation**

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# *Executive Summary*

Conservation science is a specialized activity that provides the technical support for the care and maintenance of cultural works, historical property, and collections of scholarly resources. Its central role in the stewardship of these materials, which are of paramount importance to the nation, warrants serious consideration of public financial support. This report examines the rationale for targeted investment by the National Science Foundation in conservation science research. Not only can NSF support catalyze critical exchange that would strengthen conservation science, but investment in conservation science provides important opportunities to further the goals of NSF in technology innovation and transfer, addressing critical social needs through scientific advances, and training new generations of students in the sciences.

This report describes the nature of conservation science and its support role for conservation practice. The analytical examination and study of artifact materials and construction is a central activity. These technical studies form the basis for object care and repair. When satisfactory solutions to deterioration problems are not available, focused laboratory research is done to discover the underlying processes, risk factors, and environmental conditions that put objects at risk of damage. These research studies lead to diagnostic tools and repair strategies that are then tested for efficacy and safety, and finally adapted and applied to cultural artifacts. This interchange between artifact analysis, laboratory study and development, and field applications, comprises conservation science.

The major technology areas of central importance in conservation science overlap technologies that have been the focus of NSF investment in recent years. They are:

1) material identification, fabrication, and performance;
2) material aging and degradation;
3) restoration treatment development and testing;
4) analytical and sensor technology development.

Examples of recent progress in these areas are described, and the close connections with the needs and activities in other fields are highlighted.

There are four areas of particular need in conservation science, and targeted NSF support in them could have important value both to the conservation field and to furthering NSF goals. These areas are:

1) artifact study, to gain greater knowledge of the nation's cultural and scholarly resources and their preservation needs;
2) fostering communication and collaboration between conservation scientists and scientists outside the field;
3) fundamental laboratory research studies, technology development, and field study;
4) educational activities that will exploit the appeal of conservation to engage and train students in science.

All of these areas have already been recognized as worthy of support, for they have seen occasional NSF investment in the past. Opportunities for further targeted support are described.

Finally, in order to provide a clear picture of the benefits that could be realized from NSF investment, conservation science in Europe is described. Because of sustained government investment, both from individual nations as well as the European Union, a critical mass of researchers is growing in Europe, bringing conservation scientists into partnerships with colleagues in academia and industry. A base of financial support is provided for sustained investigations to address large, multidisciplinary problems, from basic research to field implementation. Student involvement in this work has created a pipeline of new talent into the profession, and reliable employment opportunities make attractive the choice of conservation science as a career. Many of the most pressing needs of European cultural property are being addressed, and conservation science projects have also become the basis for multinational cooperative efforts.

In all these ways the National Science Foundation could play a pivotal role in enabling such fundamental change in this country. By building effective collaborations among scientific colleagues both within this country and abroad, by drawing students into careers in science through the excitement and societal value of conservation projects, and by catalyzing investment from other sponsoring agencies through targeted investments, the NSF could further its own mission through its support of conservation science. The cultural and scholarly resources of the nation, and our future as a scientific leader, would stand to benefit.

# *Introduction*

Throughout history, science and technology have been employed in the crafting, study, and preservation of cultural artifacts. Advances in material processing made possible the manufacture of ancient metal and ceramic objects. Engineering expertise was employed to construct architectural works both utilitarian and monumental. From Archimedes' discovery of a nondestructive test for gold alloy composition, to the modern use of magnetic resonance imaging to examine artifact construction, the study of objects of historical and artistic interest has always taken advantage of, and sometimes driven, the development of new noninvasive or micro-sampling examination technologies. The diagnosis of degradation mechanisms of artifacts and the development of repair or stabilization strategies is accomplished by means of multidisciplinary analysis of complex systems and innovative problem-solving. Over the past century this study of artifacts and of the means to repair or stabilize them has emerged as a specialized discipline called conservation science. Museums, libraries, and archives worldwide now employ full-time scientists to provide essential support for the efforts to conserve works of art, monuments, and the material culture of the past. Scientists in allied fields in academia, industry, and government laboratories are being increasingly called upon to transfer technological advances and expertise into the conservation field.

In the United States, as in other nations around the world, conservation science is emerging as a priority for public support, due to the increased value on collecting and maintaining cultural artifacts, monuments, and scholarly resources. Museums, libraries, and historical societies exist throughout the land and form an essential and irreplaceable part of our cultural and educational systems. At the federal level, museums and monuments in Washington, DC, as well as the Library of Congress, the National Archives, and the National Park Service, are testaments to the public commitment to stewardship of our cultural property. Federal programs, such as the National Endowments for the Arts and for the Humanities, the Institute for Museum and Library Services, and the Save Our National Treasures program, are examples of the substantial investments supporting the creation and preservation of the nation's heritage. It is reasonable that conservation science, which is so critical to effective maintenance of these public investments, should also see substantial support. Currently, conservation science activities in the National Gallery of Art, Smithsonian Institution, Library of Congress, National Archives, and National Park Service reflect that commitment. By contrast, conservation science efforts occurring in academia and industry see much less sustained support. It is in this area that organizations such as the National Science Foundation could find opportunities for sponsorship that would catalyze important participation from these experts in a wide range of technical disciplines.

Beyond the value to the conservation efforts of the nation, conservation science should also be supported because it can provide benefits that are aligned with the interests of sponsors, such as the NSF, in promoting science and obtaining broader social impacts from research investments. Collections of objects, such as mineral or biological specimens, are central to scientific study in critical emerging areas such as climate change or biodiversity. Maintenance of these collections is essential for scientific progress. Technology transfer into and out of conservation is another area which can further the goals of NSF to maximize the benefits of research investment. Conservation research also occasionally has relevance to other important societal issues. For example, study of the aging of cultural property in complex environments also bears on other issues of great importance, such as infrastructure degradation or radioactive waste storage. Similarly, the demands for sensitive and minimally invasive probes for artifacts can lead to new test and sensor technologies that can be used in many other applications. Projects in conservation science can also provide a widely appealing subject that encourages students and the public to become more engaged with science and technology. Conservation studies provide excellent opportunities to cross boundaries between disciplines and to convey difficult scientific concepts to young students.

This report will explore these issues in some detail. The various objectives and subject areas of conservation science research will be described. The rationale for NSF support within its existing structure of programs and funding initiatives will also be examined. It will be shown—and the history of occasional NSF investment in this field should make clear—that there are many project areas and collaborative opportunities in conservation science that overlap NSF objectives and interests. The NSF can play a pivotal role in bringing together research partners, leveraging research support from other sponsoring agencies, and strengthening scientific education through integrating conservation science into the mainstream of academic training. The potential benefits of such investment to the conservation field and to NSF will be demonstrated, using as an example the current investment in conservation science that is taking place within the European Community.

# *The Nature of Conservation Science*

Conservation science, like many specialized branches of study, is a discipline that is not defined by particular activities or technologies, but rather by its objectives: the preservation and restoration of objects. If conservators can be considered the doctors charged with caring for objects, then conservation scientists are the diagnostic and research support for that clinical practice. Conservation scientists must offer technical information and options for stabilizing and safely repairing all manner of cultural property and scholarly collections: works of art, ethnographic and historical collections, natural history specimens intended for systematic scientific study, books and archival collections on various media (including digital), architecture, monuments, and natural landscapes. The breadth of conservation science concerns is as extensive as the variety of properties that our culture cherishes and collects, and thus seeks to restore and maintain.

The most basic of conservation science activities is the examination and analytical study of the objects to be conserved, usually aimed at determining the constituent materials and methods used to construct an artifact. This reverse engineering of an artifact, often termed a "technical study," provides the crucial information that will underlie all subsequent decisions about preservation and repair. One key question to be answered in a technical study is which materials in an object are original, i.e., were part of the artifact when it was first made, and which materials were subsequently added by deterioration, alteration, or repair of the original. Such a determination is critical, because before conservators can proceed to stabilize, repair, and maintain an object, they must know the desired outcome of a treatment: what are the original parts of a work that are to be preserved or revealed by removing later additions, accretions, or repairs. And of course, for objects that are found to be wholly fakes, the decision may be made not to conserve them at all.

In order to determine the authenticity or authorship of a particular object, its material composition and construction are usually compared to other objects whose authenticity or authorship is known. Occasionally one might find a material or construction method that was either not known or not commonly used in a particular time or place, or that is not consistent with a particular artist's work. Finding titanium white, a pigment first made in the 20$^{th}$ century, on the Vinland Map, an artifact thought to be made in the 15$^{th}$ century, suggested it was not authentic but had been recently drawn. For objects purported to be old, one would also look for signs of the known processes of deterioration that suggest a long history. Some effects of long periods of exposure to outdoor or burial conditions, such as the intergranular corrosion of cast metals or the selective leaching of certain minerals from stone surfaces by groundwater, are impossible to duplicate, and hence these features provide evidence of age. The recent controversy over the cleaning of the Sistine Chapel paintings was at its heart a dispute over whether the removal of the darkened layers over the brightly colored paint surfaces was simply a cleaning of accumulated grime and glue repairs or the skinning of the uppermost paint that had been originally applied by Michelangelo. Only the careful study of the paints by conservation scientists was able to verify that, indeed, the cleaning treatment was removing grime and later glue additions that obscured, and were not a part of, the original paintings. It is this specialized knowledge required to interpret the findings of artifact examination and material analyses in the context of art-making practices and of natural aging processes that distinguishes conservation scientists from other material analysts.

It should be mentioned here that while all such technical studies, because they inform conservation decisions, can be considered conservation science, often these same analyses are done with other immediate objectives. So, for instance, the technical findings may be of central importance to a purely art historical investigation, and the analyses might be termed "technical art history"; or an archaeological study may use a technical approach to study artifacts, a specialty known as "archaeometry"; or the systematic study of a mineral collection may be a mineralogical investigation at its core. The analytical investigations for each of these scholarly pursuits are essentially identical, for they too are aimed at identifying materials and their alterations. Even though one may not consider these studies conservation science, since that was not their overt intent, they do provide information that ultimately informs the conservation of the objects under study, either by identifying material composition, or by examining authentic art objects that will become the basis for judging the authenticity of other objects. In this sense, even studies in allied fields can be considered contributions to conservation science.

Following the fundamental determination of what part (if any) of an object to conserve, the technical study becomes the first step in the informed care of the object, essentially assembling the medical dossier of its composition, condition, and history. Going beyond simple material identification and reverse engineering of the artifact, conservation-related examination involves examining objects for evidence of aging, damage, and instability, particularly those changes that in some way endanger important characteristics of the materials, such as their color or their strength. Common problems for which effective solutions exist may then be addressed by conservators on the basis of these findings.

But just as medical diagnoses and disease treatments cannot always be arrived at simply from examining a patient, so too diagnosis of conservation problems and development of remedial treatments sometimes require in-depth study to understand the underlying causes and to develop and test innovative solutions. These ancillary scientific research efforts, though driven by and focused on the needs of an artifact, typically occur in laboratory settings (in museums, academia, industry, or national labs) and involve stand-ins for the valuable artifacts—"crash test dummies" which can be tested more extensively with destructive test methods. Surrogate materials need to be developed that approximate as closely as possible those used in an artifact, even going so far as simulating the effects of prior aging processes and future changes that may occur upon further aging. These studies provide a fundamental understanding of aging for a given artifact, which not only gives insights into conservation problems but also guides the identification of authentic aged materials in the artifacts.

Once the chemical or physical processes that lead to stability or appearance problems have been elucidated, strategies can be developed to slow these underlying processes. This is the essence of so-called "preservation" or "collection-management" strategies, which attempt to target the known destructive influences on object materials, such as temperature fluctuations, humidity, air pollutants, and light and ultraviolet radiation, in order to provide widespread and cost-effective prevention of chronic problems. Once the risk factors for unstable conditions are known, new diagnostic tools for those risk factors or for the onset of problematic instability can be developed. New repair treatments can be devised and tested for their efficacy and safety on these surrogate art objects, just as new drugs would be tested on laboratory animals before use on humans.

Once new preservation strategies or restoration treatments have been developed, the research focus shifts again back to the artifact. New stabilization and repair methods are implemented cautiously and with monitoring of the artifacts to verify that the predicted benefits of the new methods are realized. For example, if laboratory studies indicate that certain humidity levels or lighting levels are appropriate for stabilizing the structure or color of objects, then those conditions are employed, and the objects are monitored to observe their presumably slow deterioration rates. Similarly, laboratory tests on potential repair treatments may indicate effective and safe remediation of some problematic condition. Nonetheless, the treatment must be cautiously applied to an artifact (as in a clinical trial) while closely monitoring for possible undesirable side-effects.

This interchange between artifact study and laboratory study is characteristic of applied research, which often requires in-depth understanding to guide formulation of solutions, and is illustrated in Figure 1. The artifact study focuses the laboratory work on an object's needs and the constraints that the object might pose for a viable repair treatment or preservation strategy. The laboratory study on mock-artifacts allows a deeper investigation than one could achieve with a real artifact, which can only be subject to nondestructive or micro-sampling analytical techniques. And since the laboratory study tends to involve materials that are only approximations of the materials in the artifact, it is ultimately necessary to test the relationship of the surrogate and the actual artifact, perhaps adapting the laboratory findings to the artifact in need. It is noteworthy that the fundamental laboratory work, while initially motivated by and focused on the needs of a single artifact or group of objects, has the potential for application beyond that immediate use. The discovery of the underlying cause of a problem, such as trace metal or peroxide impurities, often leads to awareness that the same factors can cause similar problems in other artifacts or in other objects besides works of art. The development of a new repair method or a diagnostic analytical tool could lead to applications to other artifacts or types of materials as well. Thus, while "closing the loop" indicated in Figure 1 suggests application of research findings to the specific artifact that spawned the research, it should also indicate potential application to other objects as well.

It is this synthesis of field study, laboratory analysis, and clinical work that comprises conservation science. Artifacts are constructed of the widest imaginable variety of materials, each of which is subject to chemical, physical, or biological deterioration processes. Thus one encounters in conservation science multidisciplinary endeavors involving chemistry, materials science, physics, engineering, and biology, in order to study various facets of a given problem. These efforts may utilize the latest technologies, or they may spur the further development of new analytical or diagnostic instruments. This impressive variety of scientific research should not obscure the common overarching objective of all these studies, improving the care of our artistic and historic heritage.

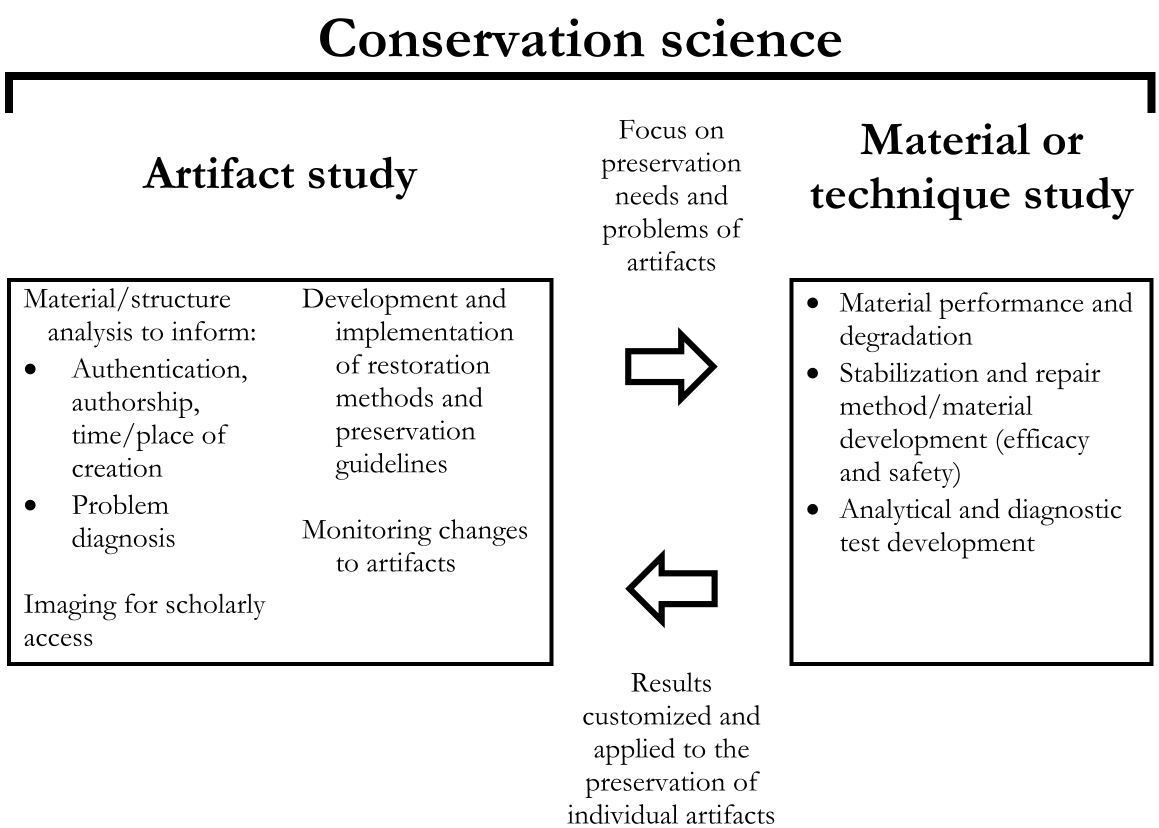


**Figure 1**

# *Conservation Science Research Overview*

Because of the wide variety of scientific activities in conservation science, it is a formidable challenge to succinctly describe active or emerging research areas. Yet just as there is an overarching objective that unifies all conservation science efforts, there are recurring themes in conservation science that can be useful in organizing an overview of current research activities. The themes have already been mentioned in the last section:

1) material identification, fabrication, and performance;
2) material degradation;
3) repair and remediation strategies;
4) analytical and sensor technologies.

It is obvious that these broad research areas are of importance to understanding the aging changes of artifact materials, devising ways to slow those changes, and developing methods to evaluate artifacts for instability noninvasively so that the artifacts are not disfigured. It is also clear that conservation science is not the only activity in which these issues are paramount. Infrastructure deterioration, radioactive waste disposal, machine vision and remote sensing, toxicology and environmental monitoring, and bioremediation of wastes are some examples of other applications that share some of these same research and technology needs. In the following discussion some of those connections will be mentioned, for it is important to recognize the commonality and the possibilities for technology transfer into and out of conservation science.

## *1. Materials identification, fabrication, and performance*

By far the most common scientific study of artifacts involves the identification of materials. This is usually accomplished using analytical techniques designed for very small samples (such as polarized light, electron, or Raman microscopies) or noninvasive examination techniques (such as reflectance spectroscopy, x-radiography, or air-path energy-dispersive x-ray fluorescence). Materials may be identified by their elemental composition, chemical constitution, or crystal structure, or some combination. While the adaptation and development of new analytical tools is an ongoing research area in conservation science (*vide infra*), material identification as it is commonly practiced utilizes conventional analytical tools. The challenge in these analyses lies in studying materials from an art object, from which no sample or only very small samples may usually be taken, and more importantly, in interpreting the analytical results. Materials comprising artifacts are often natural materials derived from plants, minerals, or animals, and processed in a number of different ways (some no longer known). These substances, which may have been easily recognizable when new, can sometimes be altered substantially through natural degradation over long periods of time. Thus these materials can exhibit variable or adulterated compositions that make difficult their identification by simple matching to modern reference materials. Consequently, as in forensic applications, efforts are made to accumulate databases of known authentic artifact materials for comparison purposes, and to understand how compositions may be changed over time so that those altered signatures can be taken into account when interpreting analytical results.

Another focus of material studies in conservation science is the elucidation of how materials were processed or fabricated, for not only can this be evidence of age or of later additions to an object, but the use of a particular technology can have historical significance as well. While there are some documentary records of the manufacture methods for many ancient art materials, for others those secrets have been lost, and it is up to modern researchers to rediscover them. Those investigations start from analysis of the artifacts and interpretation of the evidence of manufacture. For example, dendritic crystals in a bronze or a martensite phase in steel are clear indications of manufacture method, for the conditions that produce those metal phases are well known. The study of artifacts sometimes leads to discovery of new (or perhaps newly rediscovered) materials. For example, several arsenic sulfide polymorphs have recently been found in an Italian Renaissance painting, and these sulfides could be either unusual pigments used or light-induced degradation products.[1] Observations of more obvious alterations of materials, such as tarnishing of metal surfaces or blackening of white pigments on East Asian woodblock prints, lead to similar intriguing questions of whether these may be aging changes or intentional alterations by the artist. Only careful material analyses and discovery of ancient practices are likely to provide answers.

While these studies have many similarities to forensic investigations—and one might add, have much of the same popular appeal as those forensic detective stories—there are other material studies in conservation science that focus not on identification of a substance or its origin, but on characterizing its mechanical properties. Strength, stiffness, and elastic limits are all critical physical properties for materials that compose art objects. Of particular importance is the response of materials to ambient temperature and humidity and to changes in those conditions. This behavior defines the optimum environment for proper storage of objects and the hazardous conditions that can put objects at dire risk of damage. The dimensional changes and changes in stiffness that occur when temperatures or humidity fluctuate are being studied for a wide range of materials that might be found in art objects. Using these data, finite element analyses are being performed to predict the responses of composite structures in various environments.[2] Results of these analyses have been used to guide the design of appropriate climate control in museums, one of the most critical and costly of conservation decisions. On larger scales than single museum objects, material studies of traditional building materials and the engineering analyses of buildings and monuments are being used to understand the condition and risks to buildings, bridges, and monuments.[3] This information is being used to design methods to maintain or restore structures, such as the Leaning Tower in Pisa or the Statue of Liberty.

Occasionally in the course of studying artifacts one encounters hitherto unknown materials with outstanding properties or manufacturing technologies that can find use in solving modern problems. Researchers have recently discovered ancient nanotechnology, finding that the color in ancient ceramic glazes and medieval stained glass is provided from the creation of nanoparticle metal inclusions during manufacture.[4] The ancient pigment Maya blue, compounded from clay tinted with the plant dye indigo, has also been studied extensively.[5-8] Despite being composed of indigo, a dye that is not very stable towards fading, Maya blue demonstrates extraordinary resistance to fading. The mystery of this stability was found in the protected environment for the indigo dye molecules, which are intercalated within the layers of the clay mineral, palygorskite. This encapsulation renders the indigo molecule resistant to the oxidative degradation that it naturally would undergo. It has since been found that other dyes, similarly intercalated in other clays having appropriately sized pores, can also be rendered extremely stable.[9] This adaptation of ancient technology will have many applications in the coatings industry, as this new class of organic/inorganic hybrid complex pigment presents economical and environmentally friendly alternatives to metal-containing pigments. Similarly, the ancient technique of depletion gilding, invented by medieval and Incan goldsmiths to give the appearance of pure gold to gold alloys, is finding new use in developing gold membranes having controlled nanoscale pores for catalysis and separation technology.[10] Other studies continue to explore and exploit the extraordinary properties of artifact materials.

Finally, conservation science research studies are aimed at developing novel high-performance materials for use in restoration practice. Sol-gel coatings that can be applied at near-ambient conditions and that show excellent weather resistance and barrier properties have been developed and used to restore the glazed mosaic tiles on the St. Vitus Cathedral in Prague.[11] Nanocrystalline particle technologies have been explored for use as stabilizing treatments for friable stone surfaces[12] as well as to treat acidic paper materials.[13] New adhesive technologies also promise to have a profound impact on restoration, particularly in those applications where the traditional adhesives are known to have limited utility or deteriorate rapidly. These innovations in materials, part of larger efforts to improve conservation practice, are discussed further below.

## *2. Material aging and degradation*

The material studies described above are mainly the purview of analytical chemists and materials scientists. But when one seeks to understand material degradation or artifact failures, the problems demand a much wider variety of scientific perspectives. Aging processes are often chemical reactions that alter a compound and cause loss of valuable properties. Consequently, those chemical reactions have been studied extensively in conservation science just as in other industrial areas where material performance and service life are important. The nature of the chemical reactions is investigated, and risk factors for those processes identified so that one can assess the vulnerability of an artifact to suffer rapid deterioration. For example, hydrolysis is known to cause the breakdown of cellulose in paper and in cellulose nitrate or acetate photographic films, and acids are known catalysts for that reaction. Similarly, active corrosion known as bronze disease, a condition of archaeological bronzes which can lead to disfigurement or disintegration of the metal object, is promoted by soluble chloride salts within the pores of the metal. When these risk factors are identified, they become the targets for development of analytical probes and of restoration treatments.

One feature of these chemical aging processes poses a significant and peculiar challenge: most of these reactions in artifacts are extremely slow, and important deterioration processes occur over the course of decades, centuries, or millennia. It may seem evident that most artifacts that have survived centuries must be composed of materials that are relatively stable and resistant to erosion from outdoor weathering, burial, or underwater environments. In addition to intrinsic stability, artifact materials deteriorate slowly because the aging chemistries are often diffusion-controlled reactions occurring in the solid state or in nearly dry materials. The very slow degradation in artifacts does not occur in convenient laboratory timescales, so it is inherently challenging to deduce the processes that produce these aging changes. And yet despite this formidable challenge, the study of the aging of ancient artifacts poses a very special opportunity to explore extremely slow chemical and physical alterations under conditions that cannot be easily simulated. So for example, the fate of glasses containing radioactive wastes during burial over millennia will be governed by many slow processes that are difficult to predict or model. Yet the study of ancient glass objects can provide that glimpse of the possible outcome of such complex aging.[14]

While the cumulative changes of this slow deterioration are obvious, study of these processes in shorter-term laboratory studies is very difficult indeed, for available analytical tools lack the sensitivity to detect and monitor the very slight changes produced in short times. In response to this difficulty, alternative methods are adopted to stimulate those slow aging processes and produce detectable degradation in short laboratory studies. So-called "accelerated aging" tests are commonly used in conservation research—employing high temperatures or intense light to accelerate thermal or photochemical deterioration, for example—just as they have been adopted in other industries where predicting long service life of materials is important. The development of accelerated aging protocols for materials as varied as coatings, paper, mortars, and plastics has become a distinct research effort by itself.[15] Conservation science relies heavily on accelerated aging tests to understand how ancient materials have been altered over time, to predict the alterations that artifacts may undergo in the future, and to test the stability of materials that may be used to repair artifacts.

While the aging of most materials is usually the result of chemical reactions of those substances, not all degradations are the results of chemical processes alone. The blackening of the red pigment vermilion, mercuric sulfide, occurs from a light-induced phase transition from one crystalline form, which is red, to another, which is black.[16] Soiling has become recognized as a hazard to artifacts, and the deposition of airborne particulates is essentially a fluid transport problem that has been studied.[17] Moisture damage or salt deposition from moisture absorption into building structures is another transport process, and the conditions for salt crystallization that cause damaging physical stresses in stone, or development of disfiguring black gypsum crusts on buildings have been the subject of engineering studies.[3] One of the most active research areas has been in the field of biodeterioration, which has been recognized in certain obvious situations such as mold on paper artifacts or lichen growth on outdoor stone. Recent studies indicate that bacterial and fungal activity may play significant roles in deterioration that is not so obviously biological.[18] The role of biofilms in deterioration or in protection from other environmental influences has yet to be fully elucidated.[19]

Deterioration of materials is also an increasingly important consideration as object collections are used for retrospective study of newly emerging ideas, such as biological diversity or ancient climates. The fidelity of the information gained from object collections depends on their "molecular preservation," the preservation of those materials at a molecular level. So studies of genetic relationships, for example, depend on the survival of intact DNA, and even dinosaur fossil specimens are now being probed for their remnant biological matter. In anticipation of even greater use of object collections for such critical scholarly study, the conservation of object collections is developing beyond mere maintenance of the physical specimen towards stewardship of the chemical constituents in those objects as well. This much higher standard of object stability is only now becoming fully appreciated. The study of material degradation and preservation at this molecular level is a very significant new area of conservation science.

Another significant research challenge in conservation science is to better understand artifact material aging under multiple influences: to establish the relative importance of the chemical, physical, and biological mechanisms in the deterioration of a given artifact, and the possible synergisms between these aging processes. Some relationships are relatively simple—the chemical deterioration that leads to a physical property change, such as the brittleness of aging coatings or adhesives, or the physical stresses that develop from loss of volatile products of chemical aging. Chemical deterioration can also be accelerated through the application of physical stresses.[20] Photodegradation and deterioration from air pollutant exposure are not necessarily additive, and there can be synergisms between chemical and biological deterioration processes. This complexity has not been fully explored yet, and clearly such investigations require multidisciplinary teams to provide needed expertise in such widely varying subjects. As conservation science progresses, these multidimensional aging processes will surely become a focus for study that will bridge chemistry, physics, materials science, engineering, and biology.

### *3. Restoration treatment development and testing*

Conservators today are equipped with many new materials and techniques with which to clean, repair, and stabilize artifacts. Objects may be cleaned with solvents, detergents, or enzymes. Structural repairs can be done with a variety of adhesives and reinforcement materials ranging from the traditional to the modern. Appearances of deteriorated surfaces can be improved with stable retouching paints to disguise damage and patching materials to fill areas of loss. The transformations that can be effected by a skilled conservator to rejuvenate artifacts are amazing demonstrations of this very old craft.

Despite the wide variety of tools available for this work, conservators must rely on conservation scientists to evaluate the efficacy and safety of their current practices, improve those treatments, and devise new treatments for currently intractable restoration problems. Without this scientific vetting procedure, one risks restorations, even those competently done for the time, that result in disfigurement or damage to an artifact. Stone sculptures, commonly reassembled in the 19$^{th}$ century using iron supports (an accepted repair procedure at the time), now show stains, failures of the repairs, and further damage to the object as the rusted elements expand and fragment the surrounding stone. Clear cellophane adhesive tapes used on paper objects are now neither clear nor adhesive and have left stains on the artifacts. Even some newer materials that were supposed improvements, such as epoxies or poly(vinyl acetate) adhesives, have shown stability problems that not only caused further damage to the artifact with their failure, but the remedial treatment required in order to reverse these repairs puts objects at great risk of further damage. Many of these materials were originally used before a thorough scientific study of their stability, and only the passage of time could reveal their shortcomings.

Avoiding ineffective or ultimately damaging conservation treatments is one of the highest priorities of the field. Thus the examination of conservation treatments and their effects in the immediate and long-term has become one of the primary thrusts of scientific research in the field. Cleaning with organic solvents or aqueous solutions has been studied with sensitive analytical instruments to determine the efficacy on grime or varnishes, the effects on the artifact materials, and the persistence of any potentially harmful residues.[21-26] Suggested improvements of these cleaning techniques—using gels to control the contact of the cleaning agent, or tailored soaps or enzymes that target the materials to be removed while minimizing collateral attack on object surfaces—continue to be designed, tested on aged artifact materials, and examined for long-term side effects. As in the material studies cited above, accelerated aging techniques are of central importance to judge the stability of repair materials and the effects over long periods of time of their use on artifacts. Despite this high priority, there are many conservation treatments and materials that have yet to be vetted by the necessary scientific research.

In addition to this assessment and incremental improvement of existing technologies, innovative approaches are required to address problems for which currently available tools are inadequate. Cleaning of porous or friable surfaces is one such difficult problem, and researchers have been developing and testing noncontact cleaning procedures (adapting technologies also used for cleaning microelectronic and MEMS devices), such as laser ablation[27] and oxygen plasma techniques[28] for such applications. Strengthening very weak materials, such as friable stone or brittle paper, is another so-far intractable problem. Current solutions of impregnating stone with adhesives have so far proven disappointing, and paper strengthening through impregnation, lamination, or graft polymerization has not been successful. The promising new technique of "paper splitting"—peeling sheets of paper apart into two layers which are then laminated to a core of strong paper—suffers from being very abusive to the artifact and cannot be used on extremely weak materials.[29] Innovations for restoration practice are continually being offered, and each candidate approach must be carefully tailored to artifact needs and studied for possible side-effects. Completely new perspectives can lead finally to solutions to treatment problems—bioremediation of weak stone with bacteria engineered to produce calcite binding material, for example.[30] One can expect that as more innovative researchers become engaged with conservation problems, and as technology advances so that hitherto impossible tasks become feasible, these intractable restoration problems will find solutions.

As mentioned above, sometimes innovations are needed not for the repair of an object, but rather for the reversal of a past treatment. Such problems are challenging enough when dealing with single artifacts, but they can become formidable if an entire collection of artifacts or a monument or building has been treated in a way that is now deemed unsatisfactory. The recent restoration of the carved stone figures on the façade of the Notre Dame cathedral in Paris has left the sculptures discolored in irregular areas, and further treatment or remediation may be necessary to recover a pleasing appearance. In an example closer to home, the repatriation of Native American artifacts currently housed in American museums has been complicated by the past application of toxic organic and heavy-metal pesticides to those artifacts. Removal of those pesticide residues is essential for the safe handling and use of those objects, and while new technologies such as supercritical carbon dioxide extraction are promising, this problem remains unsolved.

These technology innovations and rigorous evaluations are central to scientific support for conservation practice. Mention should be made of technical support of a slightly different nature that has become of increasing importance in the field. Preservation of entire collections, rather than treatment of individual artifacts, has become recognized as an efficient means of caring for objects by avoiding severe or widespread damage caused by improper storage conditions. Thus, mass treatments have been developed for paper-based collections to neutralize the acids that would degrade the paper.[31] Climate and lighting standards are being established to define conditions that will stabilize collection materials.[32] However, some of these problems have several possible solutions that must be compared to determine the most cost-efficient care within constraints of budgets or other resources. So for instance, the question arises: should one spend preservation funds to deacidify a newspaper collection, to put it into cold storage, or to microfilm or digitize it? Each approach will offer benefits, advantages, and attendant costs, both immediate and long-term. The need for technology assessments, cost-benefit determinations, and systems analyses is increasing as more viable solutions are developed for preserving artifact collections.

## *4. Analytical and sensor technologies*

Unlike the laboratory studies of surrogate materials and restoration treatments described above, the analysis of genuine artifacts demands that one recognize that information often comes at a price: the removal of a small sample from a work of art. Obviously, such collateral damage is to be minimized, so that sampling will not leave the object disfigured. This constraint requires that artifact analysis utilize micro-analytical or noninvasive testing tools in order to identify materials, their condition and deterioration, and the overall changes in appearance or structure that mark the deterioration of the object. Today, major museums have a wide variety of tools for elemental and chemical analysis, such as x-ray diffraction and fluorescence, infrared and Raman spectroscopy, and gas chromatography and mass spectrometry, and researchers are engaged with adapting them for use on art objects. Reference libraries of analytical results for aged art materials are being compiled and new analytical protocols developed that will allow detection of several types of materials from a single sample while avoiding possible interferences from commonly encountered mixtures (such as pigment interferences with paint binding medium analyses).[33]

In addition to this adapted use of conventional analytical technologies, newer methods are constantly being explored for use in the study of artifacts. Noninvasive examination tools, using ultrasound[34] and eddy current methods,[35] optical coherence tomography,[36] and optical scanning techniques,[37] have been found useful. Micro-computed x-ray tomography has been used to observe subsurface alterations of stone caused by microbial metabolites.[38] Also of interest are imaging techniques that serve a variety of documentation and diagnostic purposes. Phase contrast synchrotron x-ray imaging has shown great potential for non-invasively assessing the structure of metallic artifacts.[39] High-resolution images, multi-spectral imaging (images collected in different wavelength bands), and the analogous hyper-spectral imaging (images taken at many contiguous wavelength regions so a reflectance spectrum can be constructed at each pixel of an image) can be used to identify pigments, to detect color changes as objects fade on display, and to provide universal images for color reproductions using any print technology, thereby offering greater accessibility of a collection for the use of scholars.[40-41]

Beyond the application of existing technologies, the analytical needs of artifact analysis push the development of new analytical instruments. Portable non-sampling Raman spectrometers are being developed for application to artifact examination.[42] A confocal x-ray fluorescence instrument using a synchrotron source has been developed (with NSF support, *vide infra*),[43] and a unit utilizing a portable radiation source is also under construction. Clearly this device, which will provide subsurface elemental analysis to expose the stratigraphy of objects with layered microstructures without removal of a sample, would be useful not only in artifact analyses but in many other applications that have similar constraints on sample removal. Surface-enhanced Raman spectroscopy, a technique that uses nanostructured silver films to amplify the Raman scattering from adsorbed molecules, is being explored for its utility in identifying light-sensitive organic pigments known as lakes.[44] Other noninvasive instruments have been developed to test for stability of colors to light or air pollutant exposure, so that object instability can be detected before significant damage is incurred from improper display or storage.[45]

There has been growing interest in the development of sensors, passive monitors, and dosimeters to detect inherent risk factors for artifact instability (like acids in paper or films) and to monitor for damaging environmental influences. New dosimeters are being developed for measuring cumulative exposure to light, especially for monitoring low doses that pose significant risks to extremely sensitive artifacts.[46] Passive monitors for airborne gaseous pollutants and particulates have been developed to address health hazards associated with indoor air pollution or volatile chemical release from consumer goods. In the conservation arena, similar devices are being developed for detecting emissions of organic compounds that pose particular hazards to artifacts.[47] Just as a "sick building" constructed with inappropriate materials presents a significant and expensive problem, construction of a gallery, display, or storage cabinet can be a widespread and expensive catastrophe. Similarly, the erosion and soiling of buildings and monuments are important concerns that are currently being studied. There is also a growing need for biosensors that can detect those microbial species that pose significant risk to artifacts and outdoor monuments. New biomolecular tools, such as Denaturing Gradient Gel Electrophoresis (DGGE) and the polymerase chain reaction (PCR), show great promise in detecting probable causative agents involved in biodeterioration.[48]

Analytical studies of artifacts are also beginning to focus on reaction products of photodegradation or other aging reactions, so-called "degradation markers," that can be used to infer age or environmental exposure histories—in essence, using the artifacts themselves as dosimeters.[49-51] As well as assessing current condition and vulnerability, such studies will of course also have great impact on forgery detection and authenticity questions. As more is learned about the aging processes of artifact materials and about the risk factors or reaction products that indicate the progress of those processes, the greater the need for rapid sensor technologies to detect and track them.

# *Opportunities for National Science Foundation Support*

With this overview of the role of the physical and natural sciences in artifact study and preservation, one can suggest activities in which NSF support could serve a vital function. Such support would not only enable the research to address priority conservation needs, but it would also further the goals of the NSF in research discovery and innovation, technology transfer, and the scientific education of young students. Key areas where support is most crucial are:

1) artifact study to gain greater knowledge of the nation's heritage and its preservation needs;
2) fostering the communication and collaboration of conservation scientists and scientists in academia, national laboratories, or industry;
3) laboratory research studies and subsequent field trials;
4) educational endeavors that exploit the appeal of artifact study and preservation to engage undergraduates and lead them to consider careers in the sciences.

In this section these areas of need will be explained in detail. Past NSF grants in these areas will be mentioned, and opportunities for possible further investment will be described.

## *1. Artifact study*

As described in the overview of the field, technical study of artifacts has two major objectives: to gain information about the object and its creators that will support the curatorial interpretation or scholarly use of the collection, and to learn about the object's condition and deterioration so that it can best be preserved. Scholars use artifact collections for their research in history, art history, archaeology, and natural science investigations, among other fields. Artifacts are also the launching point for material studies of degradation and stabilization methods, as well as the subjects for field trials of proposed treatments. Research activities revolving around artifacts have a natural constituency among scholars and investigators in the arts and social sciences. Artifact examination also has a strong appeal to scientists and students who are interested in the artifacts and the intriguing scientific questions they pose.

In addition to the examination of individual artifacts, interpretation of the analytical results relies heavily on the comparison with studies of similar objects. The context for analytical studies has become very important, and efforts to organize technical findings into databases for efficient searching and comparison are currently under way. Such a database has been compiled for infrared and Raman spectroscopic data, and an analogous effort has begun to standardize and organize results of other organic analyses such as chromatography and mass spectrometry data. Similar efforts are under way to standardize imaging examinations and to provide those data for reference purposes. These database developments are part of a broader agenda to standardize analytical protocols and to provide results to benefit a wider research community. It is likely that as imaging and data storage technologies improve, artifact examination and analysis will become more collaborative, with experts around the globe participating in interpreting results, just as medical doctors can now consult with colleagues in diagnosing problems and prescribing treatment regimens.

These resources of digital information for conservation science purposes present some of the same issues of permanence and access that are faced by digital library and archive collections around the world. The U. S. is taking a leading role in developing the technologies and methodologies, spearheaded by the Library of Congress and its National Digital Information Infrastructure and Preservation Program. In addition to the more immediate problems of information fidelity, access, security, and file format obsolescence, the preservation of the physical media on which these data are stored is clearly a continuing concern. Conservation scientists have been studying the erosion of digital data as magnetic tapes and optical media deteriorate.

***Past NSF support***

The National Science Foundation has long recognized the importance of the technical study of collections for scholarly uses and the preservation needs to maintain those collections. It has supported artifact analysis through its archaeometry program in the Division of Behavioral and Cognitive Sciences for many years, and the Division of Earth Sciences has supported studies of natural history collections, as well as providing the instrumentation that makes such studies possible. Occasionally these projects have included examinations of art objects, because of the similarities of those studies to archaeometry and mineralogy projects.[52] The NSF has also entered into a partnership with the Library of Congress in support of the Library's digital library initiatives, and NSF is currently providing funds through its "Digital Archiving and Long-Term Preservation" program. Historically, however, sponsors of art or humanities research have been expected to support the technical studies of art objects and library and archival records. Unfortunately, these organizations often cannot judge the merits of this scientific work or support costly research programs, nor do they regard the support of scientific research as their responsibility.

***Opportunities for additional NSF support***

Clearly the highly technical analytical needs in the study of art objects fall more naturally under the mandates of scientific research sponsorship provided by organizations such as the NSF. As described above, examinations of individual artifacts serve not only to inform art historical or humanities investigations, but they also are the starting points for scientific study of material processing and aging. Evidence gained from examination of individual artifacts also initiates broader studies of groups of related artifacts, in a sense population studies that lead to deeper understanding of the nature of the materials and the key factors in their deterioration. Technical studies of art objects or groups of art objects should be considered funding opportunities that will encourage discovery of new materials science phenomena and degradation mechanisms of naturally aging materials. In addition to funding the technical studies, support should continue to be provided for instrumental resources that can be shared among several institutions.

The NSF has also recently endorsed efforts to organize and make accessible data that can be utilized by a broader research community. The NSF initiative in cyber-infrastructure supports the creation of databases that strengthen scientific studies, and the effort in the conservation science field to compile analytical results of artifact materials could prove to be such an enabling technology. Advances in imaging and image storage and communication will make possible the long-distance examinations and consultations, and similar storage, organization, and access of the results of material analyses would enable similar collaborations among colleagues and students around the world. These would be significant opportunities for NSF support.

### *2. Contacts between conservation scientists and specialists outside the field*

As noted above, the interchange between the artifact analysts and specialists in material study or technology development is critical to the viability of the applied research directed towards preserving artifacts. Artifact analysts provide direction and focus on the most important problems, while laboratory investigators undertake the in-depth studies of material aging and stabilization technologies. When contact between the artifact analysts and the laboratory investigators is missing, critical technical expertise and resources needed to investigate difficult problems will be lacking, and the outside laboratory research will be poorly focused on realistic problems and thus ineffective. Further, without this interaction the possibility of technology transfer out of conservation will be remote, despite the significant expertise that conservation scientists may have on material degradation that has relevance to basic societal needs. Communication between these groups is essential, but the fact that they inhabit separate professional cultures (museums and academia/industry/national laboratories) makes contact generally haphazard and difficult.

Despite this difficulty, a number of strategies have been shown to bridge this gap successfully. Workshops and conferences have been held to bring together conservation scientists and those outside the field to communicate current needs and the available knowledge and technological advances that might be used to address those problems. Similarly, meetings have been convened to assess current knowledge and technologies. Reports of research on artifact analysis or on other conservation topics are regularly presented in dedicated sessions at national meetings of the Materials Research Society, the American Chemical Society, and the Eastern

Analytical Symposium. These gatherings serve to identify promising and important research areas that need to be pursued in laboratory studies, as well as lay the groundwork for field studies that will take the research findings into practice in the museum or archive. Likewise, a number of conservation meetings have regular sessions to report on progress in scientific research studies of relevance to the field. In 2003 the National Academy of Sciences hosted a meeting devoted to scientific investigation of art objects in their Sackler colloquium series.[53] There have been a number of focused workshops on strategic needs assessments for conservation, the Dahlem workshop series devoted to deterioration of cultural property being one example.[54-55]

### *Past NSF support*

The need for interaction between research communities and the need to foster technology transfer has been recognized and supported by many organizations, including the NSF. The NSF has engaged in such technology needs assessments for cultural properties, having hosted a bilateral workshop with an Italian delegation in Venice in 2001, "Science and Technology for Cultural Heritage."[56] This meeting was organized to bring together academic and conservation scientists to discuss and develop a research agenda addressing critical needs of cultural property, particularly buildings and monuments which pose complex materials and engineering problems. The result of that meeting was a strategic plan to focus on certain areas of research, outlines of multidisciplinary projects that would make immediate impact in those areas, and coalitions of interested participants in undertaking those projects. As an example of an effective planning meeting to clarify important directions and mobilize committed workers in key directions, the Venice meeting was special. Unfortunately that momentum was not carried forward due to the lack of funding to support the planned projects. A similar gathering, partially supported by NSF, was held at the International Conference on Materials Research and Education in Doha, Qatar, in April 2005.[57] Focusing on building collaborative partnerships among leading materials science researchers and educators in the U. S. and Middle Eastern countries, one of the four plenary sessions at this meeting was "Materials for Preserving Cultural Heritage." Like the Venice meeting, though, the Qatar meeting lacked any commitment from NSF to fund the implementation of the strategies that came from the planning sessions. This problem will be explored in more detail in the next section.

### *Opportunities for additional NSF support*

Continued support for meetings between conservation scientists and academic and industrial scientists is essential. As the number and type of artifacts that are considered cultural heritage grows, the need for technical expertise to diagnose problems and develop stabilization methods also increases. New technology developments hold great promise for artifact examination and conservation science, but only collaborations between artifact and technology specialists will lead to sensible applications of those technologies in conservation. Conferences or workshops must bring together conservation scientists who see the artifact needs and outside researchers who can identify the necessary technology approaches or pursue needed research. Such meetings can ensure that the applied research loop in Figure 1 is strengthened and that the research and development in outside laboratories remains focused on critical museum problems.

In addition to these meetings that bring together groups of participants from within and outside of conservation science, interactions should also be encouraged for individuals through support for research appointments in museums, laboratories, or cultural sites where conservation science is undertaken. While it is far from commonplace, academics do occasionally spend sabbatical appointments at museums. Conservation scientists too sometimes spend a brief research appointment at a university, industrial, or national laboratory. When such a visit occurs, it is usually supported by the scientist's employer, either the university or the museum. Yet it is clear that external support would enable more collaboration among professionals within and outside the museum world. The NSF has a natural interest in these opportunities for research advances and technology transfer; its GOALI program (Grant Opportunities for Academic Liaison with Industry) is just such a mechanism for exchanges between academia and industry. With the goal of fostering valuable interactions between groups that would otherwise have difficulty sustaining collaborative relationships, a similar program for conservation-related visits, or an expansion of the GOALI program to allow interactions between academia and cultural organizations, could have lasting benefits.

### *3. Research studies and field trials*

Efforts to establish and direct research towards conservation goals are likely to be unsustainable if support for specific research projects is not made available. Support is needed for various aspects of the work—for research personnel, equipment, user time at an instrument facility or Science and Technology Center, and so on. For conservation scientists, support may be needed for release from routine duties in order to devote concerted effort to research projects. For academics, funding must be secured that can be sustained over the years needed for students to complete graduate work.

Beyond the need to support graduate students, though, it is now clear that some conservation problems require substantial and sustained investment simply because of the difficulty of solving complex real-world problems. As with medical diagnosis of disease, an isolated occurrence of deterioration may be evidence of widespread inherent instability in a type of artifact, or it could be a problem affecting only a few objects, by virtue of some uncommon composition or storage history. To determine the nature of the problem, large numbers of works of art must be studied. Such population studies can take many years to complete, in order to locate the objects that are now scattered around the world, to obtain permission to remove samples from them, and to perform the analyses and interpret the results. Similarly, the development of new analytical protocols requires substantial investments of resources. Not only must new methods or analytical instruments be devised, but they must also undergo rigorous testing for possible interferences from other ingredients in the artifact. For example, a new method to identify the binding medium in a paint would need to be tested to determine the extent to which the pigments, other additives, or aging changes might affect the medium identification. The diagnosis of deterioration, too, poses natural complexity. The normal reductive approach to such studies—investigating a simplified system subject to a single (often exaggerated) aging influence—can only suggest possible aging factors. Eventually these reduced systems must be more closely related to an aging artifact, with complexity gradually added to the system under study until the most critical features of the artifact and its deterioration have been included. The study of a simplified system can take several years; each level of added complexity can take several more.

Thus, the solution to many critical conservation science problems will often take sustained research effort over many generations of graduate students, or the collaborative efforts of larger groups of researchers so that various facets of a research endeavor may proceed in parallel. An example of the latter approach is the recent study of paper deterioration undertaken by the American Society for Testing and Materials (ASTM).[58] In that project, separate groups set out to study heat aging, light aging, and the effects of air pollutant exposure on modern papers. Each group used samples of the same papers and tested them using the same analytical tools. That effort, which took 3 years, was comparable in scope to decades of research by individual investigators on this subject. Unlike the fragmentary earlier work, the recent project allowed compiling results into a larger meta-study of the various facets of paper deterioration, thus providing an unprecedented coherent picture of paper deterioration. Because this study was motivated by the paper industry, however, only papers currently being manufactured were included in the study. The need to obtain similarly global perspectives on the aging of other artifact materials, including historical papers, remains.

### *Past NSF support*

Beyond the artifact studies regularly sponsored through the NSF divisions supporting archaeometry and mineralogy studies (described above), the NSF has also occasionally demonstrated an interest in supporting high-quality fundamental science projects, technology development, and field studies having applications to cultural heritage conservation. The Division of Bioengineering and Environmental Systems has supported a project to develop stone stabilization treatments for Mayan archaeological sites,[59] an investigation into biodeterioration protection strategies having applicability to stone and masonry constructions generally. The Division of Materials Research has recently funded a project to develop a confocal x-ray fluorescence spectrometer,[60] a device that will have great impact in the non-destructive examination of artifacts, but which will also find many other uses, particularly in the biomedical field. The Division of Materials Science Research has also, through its Instruments for Materials Research program, awarded a grant to the Detroit Institute of Arts to acquire a Raman microscope, an instrument important in its joint work with chemists at Detroit-area colleges and universities and with industrial scientists at Ford.[61] The NSF has also sponsored a single study of the durability of artist's paint, a cooperative project sponsored under a grant to the Industry/University Cooperative Research Center on Coatings, headquartered at Eastern Michigan University, and Golden Artist Colors, Inc., a maker of artist's paints.[62]

These grants testify to NSF's commitment to support excellent analytical studies and instrument development, and they also happen in these cases to be research applied to art objects. These funded projects bring into sharper focus some key elements that are commonly lacking in traditional conservation science projects as they occur within museums. First, these projects all have significant participation by academic scientists, who can bring new expertise and perspectives to a project, as well as the involvement of students and postdoctoral fellows. That educational component, clearly a crucial element in NSF-funded research generally, is not a traditional part of conservation research done in most museums. Obviously efforts must be made to reach out for those academic interactions that will bring more student involvement, both at the graduate and undergraduate levels, into conservation science research.

A second important factor that is highlighted in the confocal x-ray fluorescence instrument development is the possibility of benefits to other fields besides artifact analysis. Particularly in projects that deal with material deterioration or nondestructive testing, there are many possible opportunities for technology transfer out of the conservation field. Those opportunities may not be fully exploited unless conservation projects involve collaboration with researchers who recognize those other applications, or unless the conservation science is published in venues that will reach a broader audience. Project support from NSF would lead to improved dissemination outside the conservation field, simply through the promotion of the work and its findings by NSF.

These features of some of the recent grants are important considerations in the planning and execution of conservation science projects. The involvement of academic scientists and their students, and a focus on potential benefits of technology transfer to other fields are critical to maximizing the impact of conservation science. It is expected that a greater integration of conservation scientists and academic colleagues, through the mechanisms described in the previous section, would eventually make such features commonplace in conservation research.

### *Opportunities for additional NSF support*

With the efforts described in the previous section to encourage connections between conservation scientists and those outside the conservation field, it is sensible to expect that the number of high-quality research projects could be increased substantially. A critical mass of investigators must be reached, so that areas of need are addressed, and so that the interaction among museum and academic scientists is self-sustaining. Funding conservation science research projects is the mechanism for building this critical mass.

The NSF could also play a pivotal role in catalyzing the organization of groups of researchers in order to address the large, centrally important challenges in conservation science. The example of the ASTM paper research program illustrates the necessary steps: meetings of conservation and technical experts to identify the research needs and likely participants; planning meetings to develop the research strategies, distribute work, and establish a mechanism for coordination; fundraising efforts; and finally the coordinated reporting and vetting of the research products. This process of fostering coordinated, collaborative research—particularly multidisciplinary research that can only succeed with this distributed effort—is by now familiar. The NSF-sponsored meeting on cultural heritage in Venice was the start of such a mobilization of coordinated research teams.

Unlike the ASTM research efforts, which ultimately succeeded because of the commitment of funds for the research, no research followed from the Venice meeting because of the lack of support for that project. The investment in the ASTM program was substantial—approximately $2 million over the three years, supporting efforts at four laboratories. While the NSF may choose not to fully support an analogous program in conservation science, it could certainly commit to the planning and organizational phases of such efforts, and commit some level of support for the research that would follow. Such a commitment would lend credibility to the project, ensure some degree of commitment from the participants, and strengthen the effort to secure additional funding from other sponsors. The Venice meeting demonstrated an eagerness among the conservation scientists and academic scientists to pursue such projects. It is hoped that a way can be identified to provide the funding that will encourage these multidisciplinary collaborations.

### *4. Educational opportunities*

Strengthening the connections between conservation scientists and academics would also provide important benefits in the training of science students. Conservation-related research projects present particular opportunities to engage students' interest in the sciences and to teach them how to apply research to address critical societal problems. The broad appeal of artifact study and art conservation problem-solving is evident when such topics are discussed with teachers and students at the secondary, college, or graduate level. There is an intuitive understanding of the value of the research goals and often a heightened enthusiasm to contribute to such worthy efforts. Artifact study and conservation research also allow students who have deep interests in the arts and science to pursue both subjects.

An applied research area such as conservation science poses problems that tend to cross disciplines and encourages examination of various facets of the problems and the innovative solutions to them; this is of critical importance in the training of scientists. As described above, conservation problem-solving requires understanding of fundamental material properties and chemical, physical, and biological degradation properties, and it also requires application of those fundamental principles to solve realistic problems. In purely academic settings, it is often difficult to create similar situations requiring such a depth of knowledge and a command of the basic principles that facilitates their application.

Many educators have recognized that artifact analysis and conservation study are subjects that can be used to enrich science education, and thus attract and retain students in the sciences. More in-depth presentations of the subject are to be found in college courses or web-based presentations on the science of art materials and the technology of art-making practice. Some academics are also establishing more formal connections with conservation scientists by jointly teaching courses or supervising research projects, sometimes in interdisciplinary centers established for that purpose. Materials science departments at Northwestern University and at the University of Arizona, for example, are creating such strong alliances between the academic scientists and the local museum and conservation professionals.

Academic scientists are not the only professionals engaged in educational activities relating to conservation: many conservation scientists too are involved in teaching at a variety of levels. Conservation scientists are occasionally asked to lecture to students at the high school or college levels and to host visits of students to museum laboratories. The training of conservators and art historians at the graduate level often involves science courses on the nature of materials and their aging. Conservation scientists, usually faculty members in academic conservation departments or adjunct faculty holding regular appointments at local museums, are charged with teaching these courses. Finally, conservation scientists are also involved in the training of new conservation scientists, who usually enter the field by taking postdoctoral fellowships, internship appointments, or entry-level jobs. As with many recent graduates, these young professionals have generally received excellent training in a scientific specialty. But since there are currently no graduate programs in which one may receive specific training in conservation science, those who enter the profession usually lack specific knowledge about artifact study and experience in guiding their own research in this field. More senior conservation scientists have an obligation to instruct and mentor these junior colleagues.

The educational mission in conservation science thus covers a variety of students, all of whom benefit from exposure to and instruction in the discipline. High school and college students discover the application of science to art, and some may choose to pursue conservation science as a career. Students studying art history or other humanities gain an understanding of the artifacts that they study as material objects, whose value as evidence may depend on their composition, state of preservation, or history of care. Conservation students are clearly better able to care for objects with a better insight into their materials, construction, and change over time. And finally, young conservation scientists require training in the specialized procedures of artifact study and experience to apply their scientific skills to important real-world problems.

### *Past NSF support*

The NSF has already recognized the value of using the multidisciplinary nature of conservation science to reach students. It has supported curriculum development and workshops for training university and college teachers who will offer undergraduate courses that describe the science in art-making practice (for example, the courses offered at Brandeis University,[63] Millersville College,[64] and at Georgia State University[65]). These workshops provide to attendees curriculum materials, references, and, importantly, contacts with experienced conservation professionals who may be able to participate in curriculum development, class activities, or future joint research projects. An analogous project to incorporate scientific concepts into training of art students has been undertaken in an NSF-supported program at Northeastern University.[66] As a result of these efforts, courses on Art and Chemistry are being introduced in colleges and universities across the country, demonstrating the general interest and appeal the field of conservation has for students, and the possibility of engaging students who might not otherwise study scientific subjects.

In addition to these activities, which have the advantage that many students can be reached through classes, the NSF also supports enrichment of student training by providing fellowship opportunities. Some of those opportunities, such as the Research Experience for Undergraduates program, support participation in NSF-funded research projects. Others, such as the pilot Discovery Corps postdoctoral fellowships, are intended as research experiences that address national needs. In fact, one of the recent Discovery Corps fellows will be working overseas on a European project examining the deterioration and restoration of historical organ pipe materials.[67]

### *Opportunities for additional NSF support*

Clearly NSF should continue to take advantage of the appeal of conservation science to interest students in science and to provide an exciting context for complex real-world problems whose solutions require depth and breadth of knowledge. The initiatives described above to foster interaction between conservation science and academia will encourage the development of courses or conferences that will lead to exposing the field to students. Similarly, should project funding become more readily available, the number of opportunities to involve graduate students in conservation projects and to expose them to the field would naturally increase.

The National Science Foundation should continue to play a role in enabling students to learn about the field. The workshops to assist teachers to develop undergraduate "science in art" courses or web materials should continue to be supported. New curriculum development initiatives should also be considered, that would include developing similar science courses aimed at graduate-level humanities students. There are also few textbooks for instruction in basic concepts in conservation science, and support for writing such texts should also be considered. Research experiences for undergraduates could also be supported to pursue conservation studies, and in addition to the benefits for the students these projects could also provide a means by which conservation scientists who may be fully obligated by service or teaching duties to pursue more scientific research.

Postdoctoral fellowship opportunities are also key opportunities to expose young professionals to a field which few may have discovered. These fellowships would be an essential means to expose scientists to this career option and would provide conservation with an influx of talented scientists. Whether a postdoctoral fellow chooses to stay in the field and pursue a career in conservation science, the experience of applying their knowledge to solve real-world problems is critically important and will be of lasting benefit. Any opportunities for supporting such postdoctoral fellowships through NSF programs, such as the Discovery Corps fellowships, should be continued.

# *Lessons from the European Experience*

In envisioning the possible benefits of sustained public funding of conservation science projects, it is instructive to examine the state of the field in European countries, which have a long tradition of support not only for the restoration and maintenance of cultural heritage, but also for the scientific research necessary to ensure effective investments in those practices. As in the U.S., the majority of conservation science research takes place in large, often publicly funded museums and cultural organizations. Many of these museums work closely together with, or contract services from, larger professional research organizations such as TNO in the Netherlands. Funding for most of this research has come from government sources in these countries.

Quite often one also observes very close working relationships between museums and local universities, particularly in the UK, the Netherlands, France, and Italy. Not coincidentally, in these countries there is also research funding, mainly from the public sector but occasionally from private philanthropies, for fostering such relationships. These projects have involved graduate students and postdoctoral fellows in the sciences, some of whom have gone on to become conservation scientists. At the University of Amsterdam there is a joint professorship in chemistry and conservation science, and graduates from this program, who were allowed to pursue their doctoral thesis research in art museums, are now on the scientific staffs at the National Gallery of Art, the Philadelphia Museum of Art, the Smithsonian Institution, and the Centre Recherche sur la Conservation des Documents Graphiques (Research Center for the Conservation of Graphic Documents) in Paris. These relationships have brought numerous benefits for the field of conservation, which has enjoyed the expertise of technical specialists outside the field and the infusion of new talented scientists whose exposure to the field was in these industrial or academic research projects. The technical fields have also been driven forward by the in-depth study of material aging behaviors and the further development of promising technologies.

A similar situation exists on a larger geographical scale in the European Community. Since its inception the EC has recognized the value of investing in cultural heritage, both for its own sake and for its impact on tourism, a major economic engine in Europe. In the EC's Fifth Framework, which distributed 15 billion euros to support a variety of research and technology development activities, conservation science was chosen as one strategic focus for its research funding. Within the *Energy, Environment, and Sustainable Development* theme, which itself had 2 billion euros budgeted, its *The City of Tomorrow and Culture Heritage* program funded 42 conservation science projects, totaling 34 million euros over various durations. An additional 10 conservation-related projects relating to digital archives and imaging were funded in another programmatic theme, *Creating a User-friendly Information Society*. Under the terms of these awards, the collaborations were multi-national and often included not only conservation scientists but also academic scientists and museum staff who could contribute the art or historical context that is crucial in the execution of the supported research. In the recent Sixth Framework, support for conservation science projects continues. Although the organization into thematic areas is not as cogent as it had been in the Fifth Framework, many of the same project activities have been carried over to this new funding cycle.

In addition to the investment in conservation science coming from the European Community, there have also been efforts organized under other intergovernmental initiatives, such as the EUREKA network, which is equivalent (on a multinational level) to the National Science Foundation's SBIR program and which has an analogous aim of catalyzing technology innovation to give European partners a competitive advantage in their businesses. The EUREKA network has funded a consortium of research centers and industrial partners to explore fundamental research into laser cleaning, including monitoring and control technologies, and to develop specialized tools for laser cleaning of artifacts.

The EC investment in conservation science has produced many benefits in collaborative research, technology development, and educational opportunities. Many of the most significant scientific advances in conservation—in laser cleaning and in treatments for degraded paper, in light/pollutant dosimetry, in aging chemistries of stone and paint materials—have come from technical specialists in academia and industry working closely with conservation scientists throughout Europe. Along with the synchrotron facility at Daresbury (UK), the new SOLEIL synchrotron in France will have a beamline dedicated to studies of art and archaeology materials. Research advances are being translated into commercial technologies, and these are being adopted in conservation practice worldwide. The EC has also supported education and training efforts. Textbooks are being written under current EC grants, and these will become standard texts in conservation training programs. Curriculum materials have been produced to facilitate training of conservation scientists, and the establishment of standards for doctoral training programs for conservation scientists is now under consideration. In addition to the collaboration being forged among museums, universities, and industrial partners, the European Community experience also demonstrates the cross-cultural opportunities presented by conservation science research. The science–art boundary is not the only one bridged in such projects. Cultural heritage conservation is truly a shared need that attracts worldwide support. The EC has found this area an important and effective rallying point for international cooperation.

This situation is being described not to give the impression that the Europeans will address all the needs of the conservation field, for the scope of the problems still exceeds the investment that the European governments are able to make in conservation science. However, the modest level of support that European conservation science has enjoyed is not only addressing critical conservation needs, it is also transforming the nature of the activity in Europe. Partnerships are being formed through grant-supported activities, bringing the museum, academic, and industrial communities together to solve critical problems with their cultural heritage.

The number of investigators and organizations focusing on cultural heritage conservation is reaching a critical mass that is beginning to: sustain a continuous focus needed to solve difficult problems; maintain a network of experts in various fields to undertake multidisciplinary projects; build a base of financial support for conservation research and development, ranging from fundamental research investigation to field implementation; and create a pipeline of new talent into the field through involvement of students in projects, development of conservation science training programs, and establishment of reliable employment opportunities. It is not only the number of conservation problems that are being addressed by the Europeans. They are seeing the maturing of the field into a mainstream scientific enterprise and career.

The National Science Foundation is in a position to effect similar changes in this country. Investment in the areas outlined in this report would have the same power to transform U. S. conservation science into a scientific endeavor more integrated with the technical specialists and educators essential to progress. Conservation science in this country must see the same maturity into a stable profession, for only in this way will the particular needs of our nation's cultural heritage be addressed. While much of our nation's museum holdings may be inherited from our European forebears, there are still significant holdings of artifacts that are distinctly American and that will require American conservation scientists to help maintain. For example, it is unlikely that conservation scientists in other lands will be engaged in the challenges of preserving space suits or other artifacts in the collection of the Smithsonian Air and Space Museum, or in addressing the difficulties of pesticide remediation of repatriated Native American artifacts. The United States will have to provide the leadership in solving conservation issues relating to this heritage of our own history.

This effort to strengthen American conservation science need not be considered a competition with European counterparts, nor simply filling the niche of specifically American conservation problems. It is also an opportunity to work cooperatively with international colleagues who share the common vision of cultural property as a vital asset. The NSF already has programs that take advantage of the vision of science as a universal enterprise, and it already has established a number of bilateral or multilateral programs for international scientific cooperation. Recent NSF grants through these international programs—the Venice planning workshop in Italy (2001);[56] the laboratory and field study of deterioration and repair of ancient structures in Egypt (2001-05);[68] the study of the corrosion and stabilization of historic stained glass with scientists in Germany (1992-95);[69] the postdoctoral fellowship for study of silk deterioration in Japan (1996-97);[70] the development of treatments for limestone in Mexico (1999-2001)[71-72]—provide evidence of the benefits that might be gained through such cooperative efforts. As the Europeans have discovered, scientific research projects that focus on cultural heritage are clearly a sound basis for forging international partnerships, bringing scientists, cultural professionals, and concerned government caretakers from other nations together to work for a common good.

# *Conclusion*

In this report, conservation science research has been described in order to clearly convey the very technical nature of the activity. It is applied problem-solving, yet the necessary research spans the range from very fundamental material studies to very practical application. Despite its context of cultural property, it is truly a scientific endeavor, and sponsorship from arts and humanities funding agencies has therefore been understandably very meager. It is natural for conservation scientists to turn to other scientists in academia and industry for collaboration and to sponsors such as the National Science Foundation for support.

The possible role of the National Science Foundation has been explored in some detail, for the NSF has historically not been very engaged with conservation science. The reason for this is not a divergence of objectives, since it should be clear from the projects that have been funded that there is ample opportunity to develop projects of significant scientific merit and broad impact. Rather, the infrequent funding of conservation science by the NSF can be viewed as symptomatic of the sporadic convergence of museum workers and academic scientists. It is the scientists in the academic community who routinely apply to NSF for funding, who bring a visible measure of accomplishment through a peer-reviewed publication record, and who engage students and postdoctoral fellows in the classroom and in the research laboratory. But the visibility of conservation in the academic community is low, and it remains difficult to establish and maintain collaborations between museum workers and academics.

It is in this integration of the museum and academic cultures that NSF can play a pivotal role. Rather than allow circumstance to dictate the contact and collaboration of academics with conservation scientists, the NSF can act decisively to catalyze that exchange. The many ways that NSF investment can affect this fundamental shift have been discussed in this report, and the benefits to be gained in conservation and in the academic communities have been detailed. The European experience provides convincing proof that a strategic focus on bringing together museum, academic, and industrial partners to engage in conservation science research can transform conservation and leverage for all participants the advantages of sustained activity in the field.

The National Science Foundation is in an ideal position to begin this strategic enterprise. As a steward of public investment in science, the NSF takes seriously its obligation to advance science to serve the public interest. Surely engagement with the scientific activities that will preserve our nation's artistic and historic heritage is such a vital public interest.

# *References*


1. Trentelman, K., L. Stodulski, and M. Pavosky "Characterization of pararealgar and other light-induced transformation products from realgar by Raman microspectroscopy," *Analytical Chemistry* **68**, 1755-1761 (1996).
2. Mecklenburg, M., M. McCormick-Goodhart, and C. Tumosa, "Investigation into the deterioration of paintings and photographs using computerized modeling of stress development," *Journal of the American Institute for Conservation* **33**, 153-170 (1994).
3. Scherer, G. W., R. Flatt, and G. Wheeler, "Materials science research for the conservation of sculpture and monuments," *MRS Bulletin* **26**, 44-50 (2001).
4. Fredrickx, P., J. Verbeeck, D. Schryvers, D. Hélary, and E. Darque-Ceretti, "Nanoparticles in luster reconstructions," in *Materials Issues in Art and Archaeology VII*, MRS Symposia Vol. 852, ed. P. Vandiver, J. Mass, and A. Murray, Pittsburgh, Materials Research Society (2005), in press.
5. José-Yacamán, M., L. Rendón, J. Arenas, and M. C. S. Puche, "Maya blue paint: An ancient nanostructured material," *Science* **273** (5272), 223-35 (1996).
6. Leona, M., F. Casadio, M. Bacci, and M. Picollo, "Identification of the pre-Columbian pigment Maya blue on works of art by noninvasive UV-vis and Raman spectroscopic techniques," *Journal of the American Institute of Conservation* **43**, 39-54 (2004).
7. Chiari, G., R. Giustetto, and G. Ricchiardi, "Crystal structure refinements of palygorskite and Maya blue from molecular modeling and powder synchrotron diffraction," *European Journal of Mineralogy* **15**, 21-33 (2003).
8. Witke, K., K.-W. Brzezink, and I. Lamprecht, "Is the indigo molecule perturbed in planarity by matrices?" *Journal of Molecular Structure* **661-662**, 235-238 (2003).
9. Chiari, private communication, 2005.
10. Ding, Y., Y.-J. Kim, and J. Erlebacher, "Nanoporous gold leaf: ancient technology/advanced material," *Advanced Materials* **16,** 1897-1900 (2004).
11. Bescher, E., F. Piqué, D. Stulik, and J. D. Mackenzie, "Long-term protection of the Last Judgment mosaic in Prague," *Journal of Sol-Gel Science and Technology* **19**, 215-218 (2000).
12. Giorgi, R., L. Dei, and P. Baglioni, "A new method for consolidating wall paintings based on dispersions of lime in alcohol," *Studies in Conservation* **45**, 154-161 (2000).

13. Giorgi, R., L. Dei, C. Schettino, and P. Baglioni, "A new method for paper deacidification based on calcium hydroxide dispersed in nonaqueous media," in *Works of Art on Paper: Books, Documents, and Photographs*, ed. V. Daniels, A. Donnithorne, and P. Smith, London: International Institute for Conservation of Historic and Artistic Works (2002), 69-73.

14. Römich, H., "Studies of ancient glass and their application to nuclear-waste management," *MRS Bulletin* **28**, 500-504 (2003).

15. Feller, R. L. *Accelerated Aging: Photochemical and Thermal Aspects,* Los Angeles: The Getty Conservation Institute (1994).

16. Gettens, R. J., R. L. Feller, and W. T. Chase, "Vermilion and cinnabar," in *Artists' Pigments*, Vol. 2, ed. A. Roy, Washington, DC: National Gallery of Art (1993), 159-182.

17. Nazaroff, W. W., M. P. Ligocki, L. G. Salmon, G. R. Cass, T. Fall, M. C. Jones, H. I. H. Liu, and T. Ma, *Airborne Particles in Museums*, Los Angeles: The Getty Conservation Institute (1993).

18. *Art, Biology, and Conservation: Biodeterioration of Works of Art*, ed. R. J. Koestler, V. H. Koestler, A. E. Charola, and F. E. Nieto-Fernandez, New York: The Metropolitan Museum of Art (2003).

19. Warscheid, E. C., and J. Braams, "Biodeterioration of stone: A review," *International Biodeterioration and Biodegradation* **46**, 343-368 (2000).

20. Bogaard, J., and P. M. Whitmore, "Explorations of the role of humidity fluctuations on the deterioration of paper," in *Works of Art on Paper: Books, Documents and Photographs*, ed. V. Daniels, A. Donnithorne, and P. Smith, London: International Institute for Conservation of Historic and Artistic Works (2002), 11-15.

21. Wolbers, R. *Cleaning Painted Surfaces: Aqueous Methods*, London: Archetype Publications (2000).

22. Erhardt, D., and J. Bischoff, "The roles of various components of resin soaps, bile acid soaps and gels, and their effects on oil paint films," *Studies in Conservation* **39**, 3-27 (1994).

23. Sutherland, K., "Solvent-extractable components of linseed oil paint films," *Studies in Conservation* **48**, 111-135 (2003).

24. Jablonski, E., T. Learner, J. Hayes, and M. Golden, "Conservation concerns for acrylic emulsion paints," *Reviews in Conservation* **4**, 3-12 (2003).

25. Hagen, E., and A. Murray, "Effects of water exposure on the mechanical properties of early artists' acrylic paints," in *Materials Issues in Art and Archaeology VII*, MRS Symposia Vol. 852, ed. P. Vandiver, J. Mass, and A. Murray, Pittsburgh, Materials Research Society (2005), in press.

26. Stulik, D., D. Miller, H. Khanjian, N. Khandekar, R. Wolbers, J. Carlson, and W. C. Peterson, *Solvent Gels for the Cleaning of Works of Art: The Residue Question*, Los Angeles: The Getty Conservation Institute (2004).

27. Teule, J. M., U. Ullenius, I. Larsson, W. Hesterman, O. F. van den Brink, R. M. A. Heeren, and V. Zafiropulos, "Controlled laser cleaning of fire-damaged paintings," in ICOM *Preprints of the 13th Triennial Meeting*, ed. R. Vontobel and A. Roy, London: James & James (2002), 252-256.

28. Rutledge, S. K., B. A. Banks, and D. L. Waters, "Atomic oxygen treatment and its effects on a variety of artist's media," in *Materials Issues in Art and Archaeology VII*, MRS Symposia Vol. 852, ed. P. Vandiver, J. Mass, and A. Murray, Pittsburgh, Materials Research Society (2005), in press.

29. Brückle, I., and J. Dambrogio, "Paper splitting: History and modern technology," *Journal of the American Institute for Conservation* **39**, 295-325 (2000).

30. Orial, G., Th. Vieweger, and J.-F. Loubiere, "Biological mortars: A solution for stone sculpture conservation," in *Art, Biology, and Conservation: Biodeterioration of Works of Art*, ed. R. J. Koestler, V. R. Koestler, A. E. Charola, and F. E. Nieto-Fernandez, New York: The Metropolitan Museum of Art (2003), 498-517.

31. Daniels, V., "The chemistry of paper conservation," *Chemical Society Reviews* **25**, 179-186 (1996).

32. Michalski, S., "Environmental guidelines: defining norms for large and varied collections," in *Preservation of Collections: Assessment, Evaluation, and Mitigation Strategies*, Washington, DC: American Institute for Conservation (1996), 28-33.

33. Schilling, M. R., and H. P. Khanjian, "Gas chromatographic determination of the fatty acid and glycerol content of lipids I. The effects of pigments and aging on the composition of oil paints," in *ICOM Proceedings of the 11th Triennial Meeting*, ed. J. Bridgland, London: James & James (1996), 220-227.

34. Murray, A., M. F. Mecklenburg, C. M. Fortunko, and R. E. Green, Jr., "Air-coupled ultrasonic system: a new technology for detecting flaws in paintings on wooden panels," *Journal of the American Institute for Conservation* **35**, 145-162 (1996).

35. Bernstein, J. R., and B. McCarthy, "Non-destructive characterization of gilded bronze using swept and pulsed eddy current techniques," in *Conservation Science 2002*, ed. J. H. Townsend, K. Eremin, and A. Adriaens, London: Archetype Publications (2003), 222-226.

36. Targowski, P., B. Rouba, M. Wojtkowski, and A. Kowalczyk, "The application of optical coherence tomography to non-destructive examination of museum objects," *Studies in Conservation* **49**, 107-114 (2004).

37. Guidi, G., C. Atzeni, M. Seracini, and S. Lazzari, "Painting survey by 3D optical scanning: The case of *Adoration of the Magi* by Leonardo da Vinci," *Studies in Conservation* **49**, 1-12 (2004).

38. McNamara, C., T. D. Perry, M. Zinn, M. Brueker, R. Müller, G. Hernandez-Duque, and R. Mitchell, "Microbial processes in the deterioration of Maya archaeological buildings in southern Mexico," in *Art, Biology, and Conservation: Biodeterioration of Works of Art*, ed. R. J. Koestler, V. H. Koestler, A. E. Charola, and F. E. Nieto-Fernandez, New York: The Metropolitan Museum of Art (2003), 248-265.

39. Young, M. L., F. Casadio, S. Schnepp, J. Almer, D. R. Haeffner, and D. C. Dunand, "Synchrotron x-ray diffraction and imaging of ancient Chinese bronzes," *Applied Physics A, Materials Science and Processing* (2005), in press.

40. Berns, R. S., and F. H. Imai, "The use of multi-channel visible spectrum for pigment identification," in *ICOM Preprints of the 13th Triennial Meeting*, ed. R. Vontobel and A. Roy, London: James & James (2002), 217-222.

41. Balas, C., V. Papadakis, N. Papadakis, A. Papadakis, E. Vazgiouraki, and G. Themelis, "A novel hyper-spectral imaging apparatus for the non-destructive analysis of objects of artistic and historic value," *Journal of Cultural Heritage* **4** (Supplement 1: LACONA IV), 330s-337s (2003).

42. Vandenabeele, P., T. L. Weis, E. R. Grant, and L. J. Moens, "A new instrument adapted to in situ Raman analysis of objects of art," *Analytical and Bioanalytical Chemistry* **379**, 137-142 (2004).

43. Woll, A. R., D. H. Bilderback, S. Gruner, N. Gao, R. Huang, C. Bisulca, and J. Mass, "Confocal x-ray fluorescence (XRF) microscopy: A new technique for the nondestructive compositional depth profiling of paintings," in *Materials Issues in Art and Archaeology VII*, MRS Symposia Vol. 852, ed. P. Vandiver, J. Mass, and A. Murray, Pittsburgh, Materials Research Society (2005), in press.

44. Whitney, A., R. P. van Duyne, and F. Casadio, "Silver island films as substrate for surface-enhanced Raman spectroscopy (SERS): a methodological study on their application to artists' red dyestuffs," To be presented at SPIE's International Symposium on Optics East 2005.

45. Whitmore, P. M., X. Pan, and C. Bailie, "Predicting the fading of objects: Identification of fugitive colorants through direct non-destructive lightfastness measurements on objects," *Journal of the American Institute for Conservation* **38**, 395-409 (1999).

46. Bacci, M., C. Cucci, A.-L. Dupont, B. Lavedrine, M. Picollo, and S. Porcinai, "Disposable indicators for monitoring lighting conditions in museums," *Environmental Science and Technology* **37**, 5687-5694 (2003).

47. Gibson, L. T., and A. W. Brokerhof, "A passive tube-type sampler for the determination of formaldehyde vapours in museum enclosures," *Studies in Conservation* **46**, 289-303 (2001).

48. Schabereiter-Gurtner, C., G. Piñar, W. Lubitz, and S. Rölleke, "An advanced molecular strategy to identify bacterial communities on art objects," *Journal of Microbiological Methods* **45**, 77-87 (2001).

49. van den Brink, O. F., G. B. Eijkel, and J. J. Boon, "Dosimetry of paintings: determination of the degree of chemical change in museum-exposed test paintings by mass spectrometry," *Thermochimica Acta* **365**, 1-23 (2000).

50. Bacci, M., M. Picollo, S. Porcinai, and B. Radicati, "Evaluation of the museum environmental risk by means of tempera-based dosimeters," *Thermochimica Acta* **365**, 25-34 (2000).

51. Odlyha, M., N. S. Cohen, G. M. Foster, and R. H. West, "Dosimetry of paintings: determination of the degree of chemical change in museum-exposed test paintings (azurite tempera) by thermal and spectroscopic analysis," *Thermochimica Acta* **365**, 53-63 (2000).

52. Harlow, G. E., D. Walker, and J. Frantz, "Acquisition of a new x-ray microdiffraction system," NSF award no. 0418088 (2004).

53. "Scientific examination of art: modern techniques in conservation and analysis," Sackler colloquium chaired by T. Wiesel and R. Hoffmann, organized by B. Berrie, E. R. de la Rie, J. Tomlinson, and J. Winter, held at the National Academy of Sciences, Washington DC, March 19-21, 2003.

54. *Durability and Change: The Science, Responsibility, and Cost of Sustaining Cultural Heritage*, Report of the Dahlem Workshop, Berlin, December 6-11, 1992, ed. W. E. Krumbein, P. Brimblecombe, D. E. Cosgrove, and S. Staniforth, New York: John Wiley & Sons (1994).

55. *Saving Our Architectural Heritage: The Conservation of Historic Stone Structures,* Report of the Dahlem workshop, Berlin, March 3-8, 1996, ed. N. S. Baer and R. Snethlage, New York: John Wiley & Sons (1997).

56. Nazaroff, W. W., and B. Amadei, "New Technologies and Cultural Heritage: A U. S.–Italian Bilateral Workshop," held in Venice, Italy, April 23-24, 2001, NSF award no. 0119379 (2001).

57. Presentations from the "Materials for Preserving Cultural Heritage" plenary session of the International Conference on Materials Research and Education, Doha, Qatar, April 4-6, 2005. Available at the web page http://materialsresearchinstitute.northwestern.edu/doha_presentations.htm

58. *Report on the ASTM Paper Aging Research Program*, American Society of Testing and Materials, West Conshohocken, PA (2001).

59. Mitchell, R., "Protection of Mayan archaeological sites in southern Mexico from biodeterioration," NSF award no. 9710577 (1997).

60. Woll, A., S. Gruner, D. Bilderback, and J. Mass, "Development of a confocal x-ray fluorescence microscope for three-dimensional composition analysis and student training," NSF award no. 0415838 (2004).

61. Trentelman, K., and L. Stodulski, "Acquisition of a Raman microscope for education and materials research relating to artistic/historic works," NSF award no. 0314685 (2003).

62. Jones, F., M. Urban, and J. Hayes, "Artist paints with improved durability," NSF award no. 9903813 (1999).

63. Henchman, M., "Developing a short course for non-scientists on the chemistry of art," NSF award no. 9254291 (1993).

64. Hill, P., "Undergraduate faculty workshop for the integration of chemistry and art into liberal arts, chemistry and teacher curricula," NSF award no. 9752769 (1998).

65. Smith, J., L. Kaplan, D. Collard, and E. Breyer, "A series of workshops in the chemical sciences," NSF award no. 0089417 (2001).

66. Bansil, A., M. Hill, C. C. Pantalone, and G. Voland, "Embedded Learning Modules (ELMO's): A new approach for teaching SME&T to non-science majors," NSF award no. 9752511 (1998).

67. Oertel, C., "Discovery Corps postdoctoral fellowship: Musical Science: Chemistry of historical organ pipe materials," NSF award no. 0412181 (2004).

68. Parizek, R., D. Gold, S. Alexander, and E. Walters, "U. S.-Egypt cooperative research: Mitigating the deterioration of monuments from the effects of evaporating shallow groundwater," NSF award no. 0420777 (2004).

69. Lanford, W. L., "U. S.-Germany cooperative research on preservation of historic stained glass," NSF Award no. 9113269 (1995).

70. Becker, M., "Japan JSPS Program: Use of pyrolysis gas chromatography mass spectrometry for assessing the state of preservation of proteinaceous materials," NSF award no. 9600262 (1997).

71. Wheeler, G. S., and C. J. Brinker, "U. S.-Mexico Cooperative Research: The development and study of strengthening agents for limestone using sol-gel and coupling agent technologies," NSF award no. 9526499 (1996).

72. Mitchell, R. M., "NSF/CONACyT: Protection of Mayan archaeological sites from biodeterioration," NSF award no. 9906337 (2000).