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Science at the Interface with Art

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ABSTRACT

The Cultural Heritage Science (CHS, formerly SCIART) Program seeks to enhance opportunities for chemistry and materials research at the interface between science and art. The objective is to promote collaboration between cultural heritage scientists, mainly located in US museums and chemists and/or materials scientists in US academic institutions to address grand challenges in the science of cultural heritage. Through the first competition, eight projects, two to three years in duration, were funded at $270,000 to 495,000 each. Every successful proposal demonstrated a clear need for collaboration with good synergy between the collaborating groups, and provided plans for meaningful training experiences for students and/or postdoctoral researchers in the field of cultural heritage science. It is anticipated that the CHS Program will continue for two additional years in a similar fashion. During this period, researchers should be able to more easily identify the disciplinary programs in materials research or chemistry relevant to their work, and their proposals will be reviewed together in panels. Proposals falling outside of the CHS specifications may be submitted directly to the relevant program/s of interest at the National Science Foundation (NSF) as unsolicited proposals. After the CHS Program ends, unsolicited proposals will remain the key mechanism for obtaining NSF funding in this research area.

INTRODUCTION

Through the years, art has been instrumental in depicting science and deepening our scientific understanding, as evidenced in numerous reports (e.g., Visualization: A Way to See the Unseen), contests (e.g., the annual International Science & Engineering Visualization Challenge), solicitations (such as National Science Foundation (NSF) 10-538: Innovations in Biological Imaging and Visualization) and funding programs (Foundations of Data and Visual Analytics). The reverse has also been true – science has been used to date, understand, conserve and preserve art and other cultural heritage objects.

In the US, most of NSF's support in the area of cultural heritage has been through its Archaeology and Archaeometry Program in the Social, Behavioral and Economic Sciences (SBE) Directorate. Still, cultural heritage objects ranging from ancient artifacts to modern art objects can undergo dynamic chemical changes over time, respond to environmental conditions and stimuli and eventually degrade and break down. There is a clear role for NSF's Mathematical and Physical Sciences (MPS) Directorate in funding basic research to understand the complexity and dynamic behavior at the molecular level of cultural heritage materials. MPS

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driven projects should also aim to develop new methods to non-destructively analyze and preserve these precious materials. Examples of NSF-funded projects in MPS include Award 0907430 to explore the microstructure of pyramid limestones and Award 0631522 to study the corrosion of centuries-old pipe organs. NSF has also provided funding of key scientific instrumentation to museums (e.g., with Award 0958786, a mapping X-ray fluorescence (XRF) spectrometer was provided to The Getty Conservation Institution, and with Award 0526926, development of a novel vibrational spectroscopy microscope was made possible at the Metropolitan Museum of Art).

Overall, the MPS portion of NSF support for research in cultural heritage science has been low, mainly due to limited laboratory research capacity in US museums. Only a small number of museums (124) and other cultural heritage institutions are even registered at the NSF (for the submission of proposals) and most do not have cultural heritage scientists and research laboratories on their premises.

The research capacity of US museums and universities has increased most significantly over the last decade primarily due to the investment of ~$50M by the Andrew W. Mellon Foundation. This foundation placed senior cultural heritage scientists in a number of US museums, supported the purchase of state-of-the-art instruments and provided postdoctoral fellowships to junior scientists who wanted to train in these vastly improved museum laboratories. Their investment has been cardinal for the development of science of cultural heritage science in the US and created the necessary framework for the NSF's new program: Chemistry and Materials Research in Cultural Heritage Science (CHS), formerly called SCIART.

In 2009, a partnership between the Andrew W. Mellon Foundation and NSF, resulted in the organization of a workshop that focused on defining grand challenges, identifying major enabling research areas and specific research needs, and outlining resources needed for advancing chemistry and materials research in cultural heritage [1]. In terms of resources, five key needs were discussed: (i) flexibility in grant mechanisms to cover the interdisciplinary nature of the field; (ii) both seed and sustained funding to attack complex problems, explore novel ideas, and nurture partnerships; (iii) development of instrumentation to advance measurement, characterization, and monitoring techniques; (iv) postdoctoral fellowships and international exchanges to develop human resources and stimulate creative ideas; and (v) the formation of centers of excellence to work at the leading edge and foster collaboration. The report also states that the support for scientific research on cultural heritage in Europe (which is predominately carried out at academic institutions) is significantly higher than that in the United States.

As a direct outcome of this workshop, NSF formed the CHS Program with a funding opportunity where collaboration between different types of institutions is a central aspect. This solicitation for proposals (NSF 10-534) sought collaborative proposals between researchers in US museums and academic institutions that addressed grand challenges in the science of cultural heritage [2]. Although Principal Investigators (PIs) have been able to submit such proposals (and related ones) to NSF prior to this solicitation, it is hoped that the CHS Program will help catalyze the collaborations needed to address problems and solutions appropriate to topical programs at NSF. A goal for the CHS Program in the coming two years is to assist PIs in identifying the best program/s at NSF for their work, so that when the CHS solicitation is no longer in effect, PIs will have a better understanding of the appropriate program/s for unsolicited proposals.

CHS PROPOSALS

Submissions to the CHS Program should be highly innovative multi-year collaborative projects that break new ground and demonstrate a high level of synergy between the collaborating investigators in one of three areas: (i) the development of new and improved analytical techniques for chemical and materials properties and structural characterization of cultural heritage objects; (ii) increasing the understanding of material degradation and aging through experimental studies of the interactions and response of cultural heritage objects to environmental parameters (bulk and surface interactions) and the development of new theoretical models to predict the dynamic properties of cultural heritage objects that would lead to their degradation while taking into consideration their molecular and micro-structural properties; and (iii) the development of new methods for materials stabilization, strengthening and repair. While the 2010 solicitation was limited to chemistry and materials research topics, it is envisioned that the program might be expanded to include additional areas of interest to the field of cultural heritage science in 2011 and 2012. A solicitation update is in preparation.

For the first year (in response to solicitation 10-534), letters of intent were requested to facilitate review activities. Full proposals were due at NSF by May 4, 2010. As outlined in the Grant Proposal Guide for NSF [3], PIs were given a choice to submit collaborative proposals either as a single proposal (with subaward/s) or through simultaneous submission of linked proposals from multiple institutions. Both approaches were used by the community. One proposal was returned without review for a non-compliance issue; it is critically important to read and follow guidelines in the Solicitation and the Grant Proposal Guide. In total, forty-one full proposals or projects were received and reviewed.

REVIEW CRITERIA for CHS

The National Science Board (NSB) mandates two merit review criteria for all NSF proposals: *intellectual merit* and the *broader impacts* for the project [4]. NSF staff also gives careful consideration to additional factors when making funding recommendations: the integration of research and education and the extent to which the project broadens and enables participation. The CHS solicitation outlined three additional review criteria: (i) the extent to which the proposal addresses a grand challenge in the field of cultural heritage science; (ii) the synergy between the collaborating groups, as evidenced in the collaboration plan between the investigators and whether researchers demonstrated a clear need for collaboration; and (iii) whether the proposed project provides meaningful training experience to students and postdoctoral researchers in the field of cultural heritage science.

REVIEW, SELECTION AND AWARD PROCESS

Proposals submitted to the CHS Program were reviewed by a panel of experts in cultural heritage science, chemistry and materials research. The panel included chemists, materials scientists and cultural heritage scientists, including individuals from other countries to enable reviewing the CHS proposals while adhering to the strict NSF conflict of interest policies. During the panel deliberations, panelists discussed the key aspects of the proposals, evaluated the proposals against the review criteria, summarized the main points, and placed the proposals into one of three categories: highly competitive, competitive, and not competitive. Program Directors

used this information, alongside programmatic considerations, to arrive at recommendations to decline or fund each proposal. Once these recommendations received Division Director concurrence, those slated for funding were forwarded to the Division of Grants and Agreements (DGA) for review of business, financial, and policy implications and the processing and issuance of the grant.

SUMMARY of FISCAL YEAR 2010 AWARDS

In total, eight projects were funded, including a pair of proposals that utilized the linked collaborative mechanism. All of the proposals that were funded satisfied the additional CHS review criteria and were ranked competitive or highly competitive by the panel. Individual projects varied in size from $270,000 to $495,000 (total) for either a 2- or a 3-year period. The total funding for the CHS Program in fiscal year (FY) 2010 was ~$3.2 million, supported in part by the Mathematical and Physical Sciences (MPS) Office of Multidisciplinary Activities (OMA), an entity chartered to facilitate and support activities that cross traditional disciplinary boundaries [5]. Proposals are not submitted directly to OMA; rather the Office works in a cooperative way with the MPS Divisions and organizations external to NSF.

Bioanalytical Technology for Art: Immunological Techniques for the Identification of Proteins and Polysaccharides in Art, Archaeological and Ethnographic Objects

Julie Arslanoglu of New York's Metropolitan Museum of Art and John Loike of Columbia University are seeking to develop and improve methodologies for accurate identification of proteins or polysaccharides in paints, adhesives, and coatings. Improved understanding derived from identification of these biological materials will enhance the informed treatment, preservation, and authentication of cultural heritage objects (Figure 1).

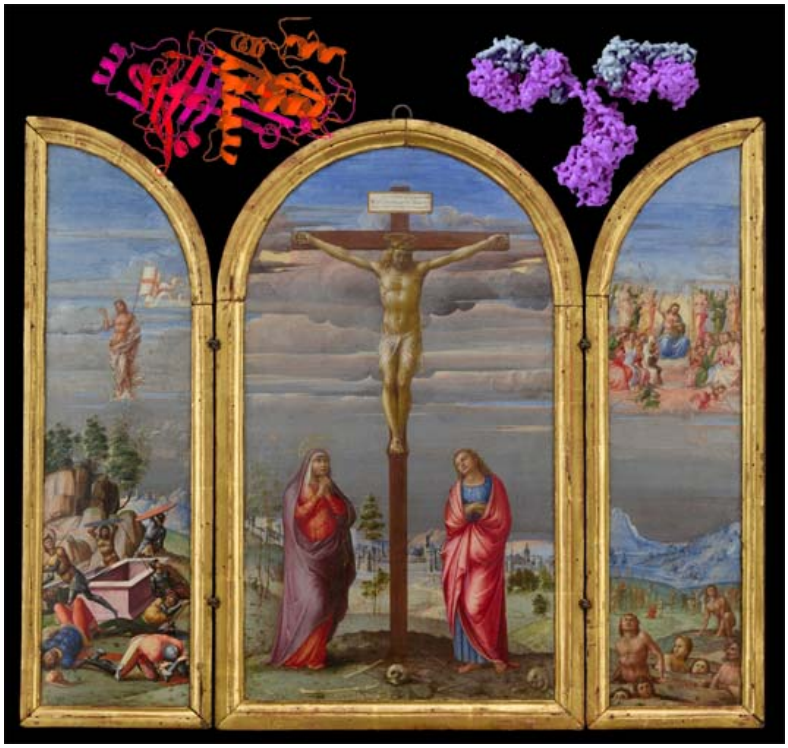

Figure 1. The Crucifixion, Francesco Granacci, Italian, ca. 1510, Tempera and gold on wood, Composite. Artwork contains animal glue in the gesso layer used to prepare the wood panels for the paint layers containing egg as a binder. Credit: The Metropolitan Museum of Art, Gift of Nancy, Carolina and Isabelle Richardson, and Purchase, Friends of European Paintings Gifts, 2006 (2006.409). Photography edited by Julie Arslanoglu from the Department of Scientific Research. Image © The Metropolitan Museum of Art.

The collaboration will provide teaching and training of students and post doctoral associates interested in the science of preservation of cultural heritage. The PIs plan to present their results through museum tours, web-based presentations on the Metropolitan Museum website, scholarly conferences and publications [6].

Table I. Funded CHS projects, institutions, and NSF support (where the managing program is underlined).

Titles	**Institutions**	**NSF Support**
1041839: Bioanalytical Technology for Art: Immunological Techniques for the Identification of Proteins and Polysaccharides in Art, Archaeological and Ethnographic Objects	Columbia University, Metropolitan Museum of Art	Chemical Measurement and Imaging (CMI) in the Division of Chemistry (CHE), Office of Multidisciplinary Activities (OMA) in the NSF Math and Physical Sciences (MPS) Directorate
1041832: Microanalytical and Non-Invasive Approaches for the Investigation of Works of Art by Surface-enhanced Raman Spectroscopy (SERS)	City College of New York, Metropolitan Museum of Art	CMI, OMA
1041827: Instrument Development and Analysis Tools for Standoff Identification and Mapping of Binders in Paintings	George Washington University, Rena de la Rie and the National Gallery of Art	CMI, OMA, Office of International Science and Engineering (OISE)
1041812: Surface-Enhanced Raman Spectroscopy for Art Research, with Theory and Education	Northwestern University, Art Institute of Chicago	CMI, OMA
1041811: Science and Preservation of the Daguerreotype	University of Rochester, International Museum of Photography and Film at the George Eastman House	Metals and Metallic Nanostructures (MMN) in the Division of Materials Research (DMR), OMA
1041809 & 1041803 Collaborative Research: Protection of Silver Objects from Corrosion using Atomic Layer Deposited Barrier Coatings	University of Maryland College Park, Walters Art Museum and Walters Gallery	Ceramics (CER) in DMR, OMA
1041808: Collaborative Research into Archeological Ceramics – High-Resolution Studies of Attic Black and Red Ceramic Slips	Stanford University, The Getty Conservation Institution, Aerospace Corporation	CER, CMI, OMA
1041853: Modified Polyhedral Oligomeric Silsesquioxane Silanols (POSS) Polymers for Stone Conservation	University of Southern Mississippi, National Center for Preservation Technology and Training	Polymers (POL) in DMR, OMA, Experimental Program to Stimulate Competitive Research (EPSCoR)

Microanalytical and Non-Invasive Approaches for the Investigation of Works of Art by Surface-Enhanced Raman Spectroscopy (SERS)

Drs. Marco Leona of the Metropolitan Museum of Art and John Lombardi of the City University of New York (CUNY) seek to use surface-enhanced Raman spectroscopy (SERS) to identify natural dyes in small samples (Figure 2). This work addresses the strict sampling limitations that make chemical analysis of cultural heritage objects difficult, magnified by the fact that the materials of interest are present in low concentrations and/or are affected by the degradation process. This team is developing sensitive and reproducible SERS substrates and new sample preparation methods, and using a broadband tunable laser to enable resonant excitation for increased sensitivity. These studies should gain additional impact through improved understanding of Raman spectroscopy. Methods developed should be readily implemented in any lab with Raman microscopes. A broader impact will be made with cross-disciplinary training for undergraduate, graduate, and post doctoral students [7].

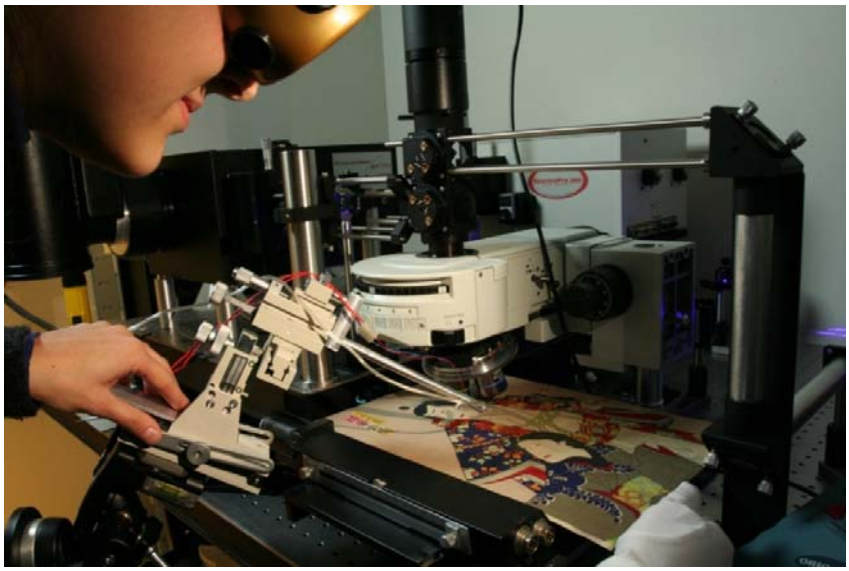

Figure 2. University of Milan Doctoral candidate Federica Pozzi, a visiting fellow in the Scientific Research Department at the Metropolitan Museum of Art, sets up a prototype inkjet device to deposit silver colloid nanopdrops on a Japanese woodblock print for non-destructive SERS analysis. Credit: Federico Carò, The Metropolitan Museum of Art.

Instrument Development and Analysis Tools for Standoff Identification and Mapping of Binders in Paintings

Professor Murray Loew of George Washington University and Drs. John Delaney and Suzanne Lomax at the National Gallery of Art are developing *in situ* methods for comprehensive examination of entire artworks, providing images ("media maps") of the pigments and binding materials used (Figure 3). Such information should provide insight into the artistic working method. An infrared imaging spectrometer with high spatial and spectral resolution is a key element. The knowledge gained should help historians better understand, and conservators better restore, important works of art. It will also illuminate how evolutionary changes can influence an artist's painting technique and style. The new instrument being developed may also have value in biomedical imaging and homeland defense, as both fields are challenged with material identification. The work will allow graduate and postdoctoral students to join collaborators in Perugia, Italy, for several months, learning their approaches to the issues and conducting some of

the benchmarking, calibration, and new-sample-library studies. In addition to publication in scientific and popular journals, results will be disseminated broadly through websites and exhibits at both George Washington University and the National Gallery of Art [8].

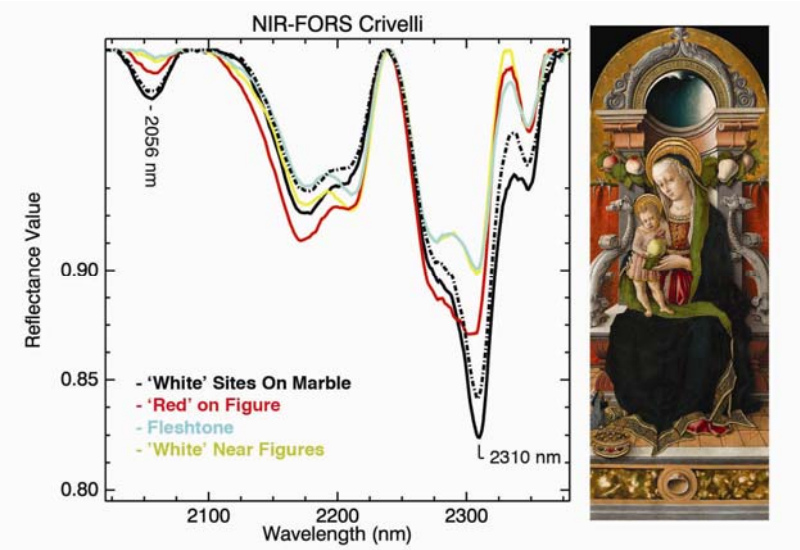

Figure 3. Near-infrared spectra (left) acquired from various sites on Madonna and Child Enthroned with Donor, by Carlos Crivelli, (c. 1470, Samuel H. Kress Collection) known to have different ratios of oil to egg tempera. Measurements made with a fiber optic probe spectral radiometer (ASD FS3). Courtesy National Gallery of Art, Washington.

<u>Surface-Enhanced Raman Spectroscopy for Art Research with Theory and Education</u>

Professors Richard Van Duyne and George Schatz of Northwestern University, and Dr. Francesca Casadio of the Art Institute of Chicago (AIC) are developing improved surface enhanced Raman (SERS) tools for determining the molecular structure of natural art pigments, dyes and their deteriorated products (Figure 4). The program seeks ultrahigh sensitivity, high spatial resolution, minimum sample damage, generality, and independence from reference libraries for identification, while minimizing exposure to light and reducing the risk of removing dyes from artwork.

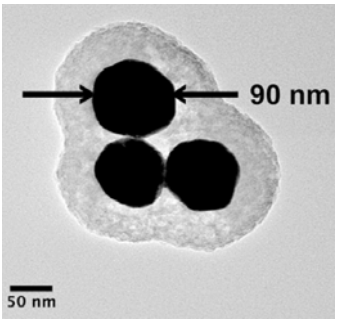

Figure 4. Depiction of nanostructured surfaces for SERS made of gold (Au) L trimer nanoantennas (Enhancement Factor (EF) around 1.7×10^8). Credit: © Nilam Shah, Van Duyne Group, Northwestern University.

Results will be disseminated to a wide public audience, using both the visual and media appeal of research stories tied to widely recognized paintings and works of art. Collaboration with the AIC's Museum Education Department will develop innovative materials and programs that illuminate the myriad connections between exploration in the sciences and interactive experiences with art. A one-week intensive summer course for teens (Inquire/Design) will be developed and offered broadly with an emphasis on attracting minority students in Chicago. The broad general public and teacher/student audience served will significantly enhance the outreach

impact of this science/art program. Students and postdoctoral associates will participate in all aspects of this unique research [9].

Science and Preservation of the Daguerreotype

Drs. Nicholas Bigelow and Hong Yang of the University of Rochester, Ralph Wiegandt from the International Museum of Photography and Film at the George Eastman House and Patrick Ravines (now at Buffalo State College) seek to use the latest material and physical sciences tools, techniques, experience and methodology in understanding the degradation modes of the daguerreotype in order to enact preservation strategies for preventing deterioration and developing restorative treatments [10]. This research may improve the understanding of corrosion of silver or silver-plated artifacts, for which the kinetics of corrosion are similar.

Students at both the undergraduate and graduate level will be trained on the ethics and analysis involved in the preservation of cultural heritage objects. In time, they will become the next generation of cultural heritage scientists and conservationists. Results will be shared worldwide with museums interested in daguerreotype preservation and disseminated through web-based applications (e.g., (http://futurity.org/) targeting high school students, exhibits at the International Museum of Photography and Film at the George Eastman House, and published in journals of interest to scientific and cultural heritage communities.

Protection of Silver Objects from Corrosion using Atomic Layer Deposited Barrier Coatings (linked collaborative)

Drs. Raymond Phaneuf, Laurent Henn-Lecordier, and Gary Rubloff of the University of Maryland at College Park and Drs. Glenn Gates and Terry Drayman-Weisser of the Walters Art Museum, seek to reduce the corrosion rate of silver artifacts without affecting its appearance or composition by using atomic layer deposition (ALD) to develop a novel multilayer, multifunctional barrier coating for silver objects (Figure 5) [11]. The reversibility of ALD metal oxide coatings will be evaluated to determine if either the deposition or the removal of thin layers of metal oxides on silver significantly changes the physical characteristics or chemical composition of the silver surface. The direct impingement of oxidant molecules through pinholes in barrier coatings will be prevented by depositing multiple layers of alternating oxides of aluminum and titanium. The additional challenges in this project include: achieving a colourless barrier, impeding further tarnishing, and conformal coating of three-dimensional objects with high aspect ratio features.

Figure 5. Walking Lion by Antoine-Louis Barye created in 1865. Image of lion from 1988 prior to being cleaned for an exhibition (left) and after cleaning (right). Credit: Walters Art Museum

Results of this work will be shared with the global museum conservation community through publications, courses, websites and presentations. For example, results will be included in lectures in both technical and nontechnical courses at the University of Maryland. Students at both the graduate and undergraduate level will be trained in cutting-edge ALD film fabrication and characterization techniques, and in museum conservation practices. A program at the Walters Art museum for introducing the public to the role of science and conservation, "Making the Invisible Visible," as well as the Conservation Window (http://thewalters.org/conservation/window.aspx) activities will provide unique dissemination for the research outcomes.

High-Resolution Studies of Attic Black and Red Ceramic Slips

Drs. Karen Trentelman and Marc Walton of the Getty Conservation Institution, Dr. Piero Pianetta of Stanford University/ SLAC National Accelerator Facility, and Dr. Mark Zurbuchen of the Aerospace Corporation seek to investigate the chemistry and material structure of archaeological ceramics at a unique level of detail using state-of-the art high-resolution analytical technologies (Figure 6) [12]. This research will measure the composition, morphology and chemical state distribution of iron minerals comprising ceramic slips using the high-resolution techniques of laser ablation inductively coupled mass spectrometry (LA-ICP-MS), X-ray absorption spectroscopy (XAS), X-ray diffraction (XRD), transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDXS). Through this project the knowledge of the materials and methods used to create Attic pottery is expected to be advanced, and new insight will be provided into ancient workshop practices, thereby impacting a diverse range of fields including materials science, chemistry, archaeology, art history and art conservation.

Figure 6. J. Paul Getty Museum Associate Conservator Jeffrey Maish examining an Attic black figure kylix under a binocular stereo-microscope. Credit: J. Paul Getty Museum.

A post-doctoral researcher will receive a uniquely integrated experience in cultural heritage, academic, and industrial laboratories. Findings will be disseminated through targeted publications and conferences to reach audiences in a number of scientific disciplines including ceramics, chemistry, materials science and archaeometry. Integrated outreach programs will educate and inform students at all levels and the general public about how science contributes to our understanding of one of the most important ancient civilizations in Western human history.

Modified Polyhedral Oligomeric Silsesquioxane Silanols (POSS) Polymers for Stone Conservation

Drs. Derek Patton of the University of Southern Mississippi and Mary Striegel of the National Center for Preservation Technology and Training seek to address the need for understanding the interface between polymers and stone materials to develop an improved treatment of stone degradation based on POSS polymer systems [13]. The PIs have devised a novel approach to stone consolidation by infusing the stone objects with a liquid monomer offering high depth of penetration, which can then be cured by photopolymerization.

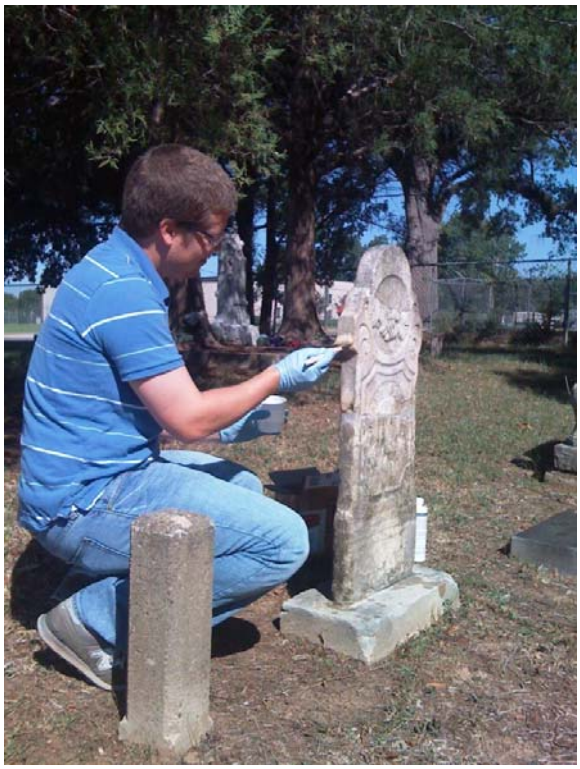

Figure 7. Graduate student, Bradley Sparks, applies a commercially-available stone consolidant by brushing the solution onto a stone grave marker. Credit: Derek Patton, School of Polymers & High Performance Materials, University of Southern Mississippi.

The research project is highly interdisciplinary and will provide both graduate and undergraduate polymer science students with a unique opportunity to collaborate and interact with an industrial leader in nanomaterials (Hybrid Plastics) and with the only preservation research and technology center (National Center for Preservation and Training Technology, NCPTT) within the U.S. National Park Service. The project also works with K-12 students in a variety of hands-on polymer science activities that focus on the conservation of historical items. The results of the work will also be widely disseminated by way of webinar and podcasts to broaden public awareness of the preservation of important cultural heritage items.

SUMMARY and CONCLUSIONS

The research funded in the first year of the CHS Program is innovative and has a high potential for impact on the conservation of cultural heritage; it will be exciting to monitor the progress of these projects in the coming years. Towards this goal, NSF plans on convening the awardees at regular intervals to review both results and challenges. It is anticipated that these NSF-funded projects will attract and engage a larger sector of the public because of their connection to art and their visibility at museums.

NSF's support for scientific research in the field of cultural heritage has been significantly expanded through the CHS Program. Although two of the CHS non-academic researchers have previously been recipients of NSF instrumentation awards, none were a PI or co-PI on a previous NSF research grant. In one case, a museum had not previously received an NSF award. One goal of the CHS Program is for PIs to use the program solicitation as an opportunity to determine the relevancy of their work to various NSF programs and divisions. After the conclusion of the CHS Program, it is anticipated that the main NSF avenue for support of research activities in this arena will come from unsolicited proposals submitted directly to individual programs and divisions at the Foundation.

The 2011 CHS program solicitation has been posted with a deadline of May 11, 2011 [14]. Subject to the availability of funds, the CHS Program will continue to fund projects in materials research and chemistry for an additional competition, with possible expansions to other disciplines and internationally.

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REFERENCES

1. The Andrew W. Mellon Foundation, http://mac.mellon.org/NSF-MellonWorkshop.
2. National Science Foundation, Chemistry and Materials Research at the Interface between Science and Art (SCIART), Program Solicitation, NSF 10-534, http://www.nsf.gov/pubs/2010/nsf10534/nsf10534.htm.
3. National Science Foundation, "Grant Proposal Guide", NSF Proposal Processing and Review, Chapter 3, http://www.nsf.gov/pubs/policydocs/pappguide/nsf09_1/gpg_3.jsp.
4. National Science Foundation, Chemistry and Materials Research in Cultural Heritage Science (CHS), http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503478.
5. National Science Foundation, Office of Multidisciplinary Activities (OMA), http://www.nsf.gov/mps/oma/about.jsp.

6. J. Arslanoglu and J. Loike, Bioanalytical Technology for Art: Immunological Techniques for the Identification of Proteins and Polysaccharides in Art, Archaeological and Ethnographic Objects, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041839&WT.z_pims_id=503478.
7. M. Leona and J. Lombardi, Microanalytical and Non-Invasive Approaches for the Investigation of Works of Art by Surface-Enhanced Raman Spectroscopy (SERS), http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041832&WT.z_pims_id=503478.
8. M. Loew and J. Delaney, S. Lomax, Instrument Development and Analysis Tools for Standoff Identification and Mapping of Binders in Paintings, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041827&WT.z_pims_id=503478.
9. R. Van Duyne and G. Schatz, F. Casadio, Surface-Enhanced Raman Spectroscopy for Art Research with Theory and Education, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041812&WT.z_pims_id=503478.
10. N. Bigelow and H. Yang, Science and Preservation of the Daguerreotype, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041811&WT.z_pims_id=503478.
11. R. Phaneuf, L. Henn-Lecordier, G. Rubloff, G. Gates and T. Drayman-Weisser, Protection of Silver Objects from Corrosion using Atomic Layer Deposited Barrier Coatings, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041809&WT.z_pims_id=503478. http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041803&WT.z_pims_id=503478.
12. K. Trentelman, M. Walton, P. Pianetta, and M. Zurbuchen, High-Resolution Studies of Attic Black and Red Ceramic Slips, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041808&WT.z_pims_id=503478.
13. D. Patton and M. Striegel, Modified POSS Polymers for Stone Conservation, http://www.nsf.gov/awardsearch/showAward.do?AwardNumber=1041853&WT.z_pims_id=503478.
14. National Science Foundation, Chemistry and Materials Research in Cultural Heritage Science (CHS), Program Solicitation, NSF 11-528, http://www.nsf.gov/pubs/2011/nsf11528/nsf11528.htm.

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