Integrating Imaging and Analytical Technologies for Conservation Practice

Report of an Experts Meeting held September 10-12, 2013

The Getty Conservation Institute

This meeting was generously supported by Dan Greenberg and Susan Steinhauser

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Front row: Jayashree Kalpathy-Cramer, Ioanna Kakoulli, Paola Ricciardi, Karen Trentelman, Catherine Patterson, Elena Biondi, Holly Rushmeier, Jim Coddington

Second row: Ruven Pillay, Koen Janssens, Burkhard Schäfer, Robert Erdmann, John Henry Scott, Simon Cherry, Jan Stubbe Østergaard, Curtis Wong, Jeanne Marie Teutonico

Back row(s): Dale Kronkright, Eric Miller, Patrick Treado, John Delaney, Robert Stein, John Cupitt, Robert Hurt, Giacomo Chiari, Dennis Wuthrich, David Saunders, Tim Whalen, Bob Page, Paul Strupp, Murray Loew

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Executive Summary

Goal:

To improve the contribution of scientific and technical studies to the conservation and understanding of works of art through the computer-assisted integration of imaging and analytical data, together with visual observations, in a way that facilitates the extraction and sharing of new information by a broad community of users.

It was agreed at the meeting that this goal could best be achieved by changing the way we work to a more global community, one in which data are more freely accessible. This would not only facilitate integration of different types of data, from different researchers at different institutions, but would enable broader, more meaningful and new types of research to be conducted. In short: ***a new paradigm needs to be created for the way data are collected, stored, accessed, shared, analyzed and interpreted.***

Meeting Structure:

The invited participants consisted of experts from a variety of fields, including art history, conservation, conservation science, image science, computer science, data mining, data integration, and data visualization. In addition to the expert participants, observers from the J. Paul Getty Trust and potential funding agencies were in attendance. The group met over 2½ days at the Getty Center, beginning with tours and a social event on the first evening followed by 2 days of small-group discussions. The discussion themes were selected to identify (i) the state of the field in cultural heritage research practice and computer-assisted technologies, (ii) the benefits that would be provided by an integrated data system, and (iii) specific priorities for action (both long- and short-term).

The diversity of voices and experiences made for lively and productive discussions and served to stimulate new professional partnerships among the participants. Following the meeting, many of the participants expressed strong interest in remaining active in developing the new paradigm that was envisioned at the meeting.

Recommendations:

To promote the adoption and sustainability of a new paradigm for cultural heritage research, the participants discussed the main types of research questions and data important to cultural heritage, the software approaches that would best be adapted to these data, how to begin to bring data (and people) together, and the education, training and support that would be needed. Descriptions of the outcomes of individual discussions are detailed in the body of this report, but the major areas identified as being most promising/necessary for future development/adoption of an integrated data system are:

- ***Develop standards to ensure successful wide-spread integration***
    - *Metadata*. Quality metadata are critical to success, and standards need to be developed. Small working groups should be formed to make an initial determination of minimal metadata requirements. Additional meetings should be held with small groups of experts representing selected important domains in cultural heritage data (e.g. spectroscopy, imaging, paintings, etc.), to define critical domain-specific metadata.
    - *Vocabulary*. Similarly, a common vocabulary needs to be developed. Small working groups should be convened to determine minimum vocabulary standards to coordinate with the metadata standards (may be the same groups as defining metadata standards).
    - *Data Sharing*. Leaders from institutions willing to spearhead this effort should meet to establish commonly agreed upon guidelines and policies for data sharing.
- ***Conduct pilot projects to identify most promising directions for growth***
    - Pilot projects should be relatively short term, so that they can respond to the changing nature of computer technologies in a timely fashion and provide input for revising the metadata, vocabulary and data sharing standards. This approach will encourage early adoption and steady, iterative growth.
    - Example initial pilot project: Give a well-defined data set (or sets from 3 different institutions) to a small group of software developers and scientists to (i) test methodologies and evaluate suitability of current practices for data/metadata handling, sharing, searching and querying, (ii) evaluate the type and degree of added value, and (iii) make recommendations for improvement/change.
    - Subsequent pilot projects, based on the outcome of the initial project(s) should be developed to revise protocols for specific applications/objectives.
- ***Build and sustain an active community of users and developers***.
    - Sustainability will require ongoing support (both technical and financial) and education. Major ideas presented included the need for establishing dedicated support centers (for education, training and technical support) for new integrated platforms, and engaging universities to begin inculcating the idea of sharing data to enable data integration in curricula for *all* cultural heritage professionals (conservators, art historians and scientists).
- ***Identify funding sources (public and private) to support new research initiatives that capitalize on the interdisciplinary nature of the proposed work.***
    - This report is expected to act as a guide for researchers, funding agencies, and entrepreneurs who wish to advance the use of computer aided technologies in conservation.

Experts Meeting Report: Integrating Imaging and Analytical Technologies for Conservation Practice

Overview

Researchers in the field of conservation – both those engaged in conservation science and practicing conservators – gather or generate an enormous amount of information (data) during the course of an analysis or treatment campaign on an object, artist, or site. The same is true for curators and art historians, who not only have access to vast repositories of information through research resources such as digital archives, but are also increasingly incorporating the technical information generated by conservators and conservation scientists into their work. This ability to capture or generate information is rapidly surpassing the ability of a single researcher, or even a small group of researchers, to fully analyze and understand the information that is generated. In fact, the discovery of subtle phenomena or relationships may be lost in an overwhelming amount of data.

The motivation and purpose of this meeting, therefore, was to explore the extent to which computer-assisted technologies may help cultural heritage researchers integrate different types of data, including those from different researchers and different institutions, in a way that facilitates the extraction, sharing and understanding of new information by a broad community of users. One of the main outcomes from the meeting was a general agreement that, for such a system to be successful, a paradigm shift would be required in the way that data are collected, stored, accessed, shared, analyzed and, perhaps most importantly, interpreted. The result would be a more open, collaborative, global research community, in which the valued intellectual product is not the data itself, but the scholarly distillation and interpretation of that data, which will bring new insights to the conservation and understanding of cultural heritage.

Many fields are exploring the concept of mining "big data." While the data in cultural heritage research may differ from that of other fields, there is much that can be learned from all data-rich fields, both from scientific disciplines such as astronomy, medicine, and pharmaceutics, and business-oriented disciplines such as gaming, finance, and marketing. The participants for the meeting, therefore, were selected to include representatives from a wide variety of disciplines and institutions. A total of thirty experts participated in the meeting, held September 10-12, 2013 at the Getty Conservation Institute in Los Angeles, California, representing the fields of conservation, conservation science, art history, imaging science, data visualization, data and information science, astronomy, computer science, medicine, and software development. Institutions represented included cultural heritage institutions (museums and research/teaching organizations), universities, government agencies, and corporations (both large and small).

Research on works of art can generally be categorized as falling into one of five broad (and often overlapping) areas: conservation issues, attribution questions, determination of provenance, elucidating historic technologies, and understanding and predicting change over time. Underlying work in each of these areas is the need of researchers to find connections between different art objects, materials, observations, or points in time. Data, whether in the form of written descriptions, images obtained using different portions of the electromagnetic spectrum, or analytical data such as chemical spectroscopy, are an important means to making these connections.

Making such connections is facilitated by the availability of directly comparable data sets. However, variation in the completeness of data sets (and the accompanying metadata) means this is often difficult or impractical. The inherent limitations of working with unique and culturally important materials – material heterogeneity, structural complexity, the limited number, size, and types of samples, and, most importantly, the preciousness of the materials – often dictates that non-invasive or minimally-invasive techniques be employed, and may disallow certain techniques altogether. Metadata – data about the data – is also critical for integration to be effective, and (when present) it too may suffer from having been collected in different forms (or formats), or using non-standardized vocabularies. These limitations often inhibit the ability of researchers to collect the same suite of information from multiple works of art and consequently, the "completeness" of the data set may vary considerably from piece to piece, and from study to study. Furthermore, important historic data may only be available as physical objects (e.g. correspondence, photographs or sketches), that would need to be converted into digital form before they could be integrated. One of the major challenges for data integration, then, is to successfully compare such disparate data sets in order to facilitate broader investigations by extrapolation of research implications to other objects or sites.

Because of the visual nature of most works of art and cultural heritage objects, imaging technologies will undoubtedly serve as a foundation for any integrated data system that may be developed. Images may serve as a framework to integrate not only different types of imaging technologies with each other, but other types of analytical and descriptive data as well. In some cases, integration of certain imaging and analytical data is already achieved through the measurement itself – for example large-scale XRF mapping or multi-spectral imaging. Such inherently integrated systems will provide a built-in linking of data to specific locations on an object, which will simplify the integration of data from different types of measurements.

For those data not inherently integrated, a digital image can serve as a control point to aggregate the different types of data associated with that object, and unique locators can be created to connect data to specific area(s). Utilizing a "region of interest" on an image, for example, a user will be able to retrieve all the data/metadata related to the selected area, as well as any associated links. However, advances in computer-assisted technologies may be necessary to facilitate this. Advances in image processing may also be necessary to improve, for example, automatic registration algorithms and methods for image comparison and fusion. Tailored data processing, the interpolation of sparsely sampled data, and the integration of existing data with new data may require research into data mining techniques and statistical analysis of results.

The ability to utilize data visualization techniques will be another powerful outcome of data integration. Because of the inherently multidisciplinary nature of most cultural heritage research, potential users include scientists along with researchers from a diverse range of fields including art conservation, art history, archaeology, anthropology, architecture or other related disciplines. Even without broad integration, the importance of images and data visualization for cultural heritage researchers is already apparent through projects such as the Bosch Project,[1] ARCHES[2] and large-scale XRF mapping.[3] The ability to convey data via images is a powerful tool for aiding communication between scientists, conservators and curators: images are a common language. Visualizations that capitalize on integrated data sets will need to be able to handle large quantities of data and be powerful, yet intuitive, to be both broadly used and widely accessible, which may require innovation in, or adaptation of, existing visualization technologies.

The adoption of a new paradigm of collecting, storing, sharing, and interpreting collections of data relating to cultural heritage will not only require technological advances – it will require advances in human and institutional behavior. Technological resources and methodologies, such as social media, cloud computing and linked open data can assist in fostering communication between users and developers and create a more global research community. Mechanisms will need to be created to establish broadly accepted guidelines for data and metadata collection and storage, to educate and train users, and to develop expanded institutional policies regarding sharing and intellectual property.

[1] See http://boschproject.org/; a project to study and document Hieronymus Bosch's paintings in detail, using modern, standardized methods and allowing exploration of the painted surfaces via innovative synchronized image viewers.

[2] See http://www.getty.edu/conservation/our_projects/field_projects/arches/arches_overview.html; a project to develop for the international heritage field an open source, web- and geospatially-based information system to inventory and manage immovable cultural heritage.

[3] See http://www.youtube.com/watch?v=spFz_4jaOzQ&feature=youtu.be; large scale X-ray fluorescence mapping of a surface allows visualization of elemental compositions in the spatial dimension.

Experts Meeting Report: Integrating Imaging and Analytical Technologies for Conservation Practice

Detailed Meeting Summary

Meeting Introduction

The meeting was opened by Karen Trentelman (GCI), who reviewed the goals for the meeting and outlined the upcoming discussion themes. Based on earlier meetings with conservators and curators, she outlined the areas of research identified as most in need of, and likely to benefit from, an integrated data approach – conservation practice, attribution, provenance, historic technologies and change. For example, the integration of chemical and physical information (e.g. composition, color) with imaging data might help in the reassembly of pottery sherds. The use of technologies such as facial recognition software might assist traditional means of making attributions by providing additional criteria. The integration of data from related objects in the collections of different institutions may be critical for understanding broader aspects of artistic practice and ancient trade. And the integration of imaging and chemical data to extrapolate information gathered from discrete spots to create a representation of the entire object, from which informed models to predict aging behavior (e.g. color change) may be created.

Opening Discussion: Defining "data" and identifying drivers for cultural heritage and software/technology fields

The opening discussion was designed to provide the participants with the opportunity to begin to get to know each other, and to develop a common vocabulary. Catherine Patterson (GCI) reviewed some of the materials provided to the participants in the "Data Dossier" section of the meeting materials, emphasizing that they should think about the different forms, scales and uses of data. For the break-out session, the participants were asked to define "data" and identify the important motivating factors/desired outcomes of data integration, as well as the foreseeable challenges.

Broadly, the participants defined "data" as anything that can help facilitate comparisons or analysis. Metadata – the minimum information set that describes data – was identified as an important class of information in its own right, critical to the success of data integration and discoverability. It was universally agreed that improved systems of data integration will be valuable both for improving the ability of researchers to synthesize information and for expanding the reach/impact of collected data.

Definitions of data and important considerations:

- Output from analyses, measurements, records of physical phenomena;
- Metadata: instrument settings; record of data processing, transformations, manipulations (data provenance); annotations; context; coordinate systems;

- Data forms include: analog vs. digital; raw vs. processed; lower vs. higher order; macro vs. micro, quantitative vs. qualitative; observations vs. intrinsic properties; historic/archived; chemical; multi-dimensional (e.g. data stacks/image cubes); descriptive (hand written/digital reports); spectra (all types); technical images (all types), temporal.

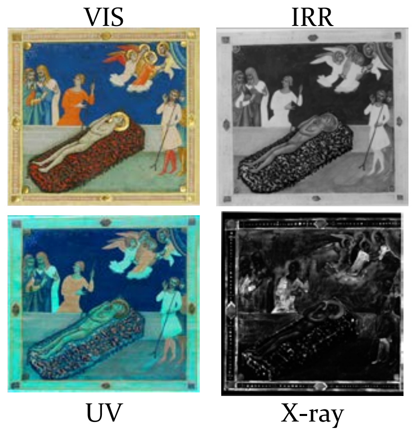
Benefits of data integration, motivating factors and desired outcomes:

- Better input: integration of multiple data types into a consistent, accurate, and useful representation (data fusion); linking of data to facilitate comparisons/correlations; facilitate predictive modeling; larger data sets will provide better statistics, with concomitant increase in confidence in results;
- Better output: improve workflow (become iterative, flexible and object/question driven); improve efficiency (increase timeliness, especially with respect to conservation treatment questions); allow extension to sites/field work; add value to existing data through linkages to other data;
- New insights and increased scholarship (scholarship isn't raw data, it's the interpretations made from the data);
- New means of communication/dissemination to broad group of stakeholders.

Challenges to data integration:

- Insufficient/inconsistent collection of metadata; lack of metadata for historic data; practical difficulty in capturing annotations/interpretations; difficulty in incentivizing metadata collection;
- Lack of image registration capability (spatial-temporal); lack of consistent, internally coherent spatial coordinate reference system;
- Lack of standards for acquisition, storage and archiving of data and metadata; lack of schemas, ontologies and controlled vocabularies; lack of unique identifiers;
- Inconsistent quality/trustworthiness of data; lack of reproducibility due to lack of metadata;
- Obsolescence of file formats/software (can be overcome if a description of how the data are collected/organized exists);
- Institutional/legal roadblocks to data sharing; issues of data ownership; private/open data;
- Data/metadata in different languages (both computer and human).

Conservation Research: Example Data Types



PACINO DI BONAGUIDA
Active ca. 1303–ca. 1347

The Martyrdom of Saint Lawrence
ca. 1340 (text in Italian)
Tempera and gold leaf on parchment
19 × 20.8 cm (7½ × 8³⁄₁₆ in.)

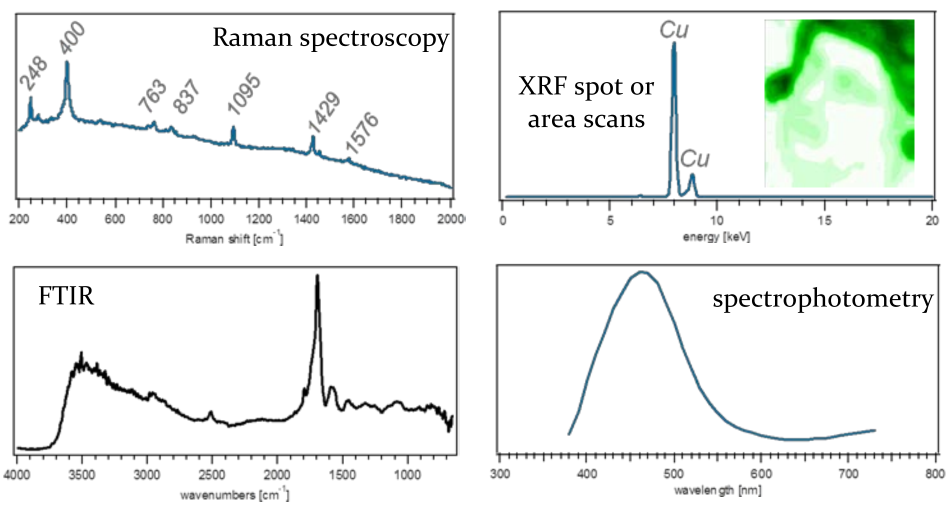
TEXT *Recto:* CI – "...diddio sire. a lo qual se[m]pre/ ti piacque il servire. laon/de se incoronato. nerregno..."[1]

COLLECTION Los Angeles, The J. Paul Getty Museum (Ms. 80b; 2006.13)

PROVENANCE Compagnia di Sant'Agnese, Florence, ca. 1340; Carlo Micheli, Paris; to Fritz Mayer, 1906; [sold to L. Soullié, Paris]; Robert Forrer, Strasbourg; [sold C. G. Boerner, Leipzig, December 4, 1911, lot 35]; to Jacques Rosenthal, Munich (cat. LXXVI, 1918, no. 28); Baron Marczell von Nemes, Munich; [sold Frederick Muller & Cie, November 13–14, 1928, lot 102]; to Daniel George van Beuningen, Vierhouten, the Netherlands; to a private collection by the early 1980s; [sale, Christie's, London, June 7, 2006, lot 11]; J. Paul Getty Museum, 2006

JPGM and AGO

In the field of cultural heritage science, data can take many forms. In broad terms, data can be *descriptive* (generally text-based), *spatial* (generally presented as an image), or *analytical* in nature (generally presented as a spectrum or other graph, stemming from material analysis). These categories are not absolute, and in many cases the data types cross boundaries, or intersect, with one another. For example, a calibrated image may be considered a form of analytical measurement, but is presented visually. The labels on a graph are a form of descriptive data, or the results of a chemical analysis may be presented in text form. One may encounter a sketch of an object (spatial), accompanied by descriptive text that contains much of the information content of the sketch. Analyses performed on a single object, such that performed on the illuminated manuscript leaf *The Martyrdom of Saint Lawrence* (by Pacino di Bonaguida), shown here, provides a glimpse of the variation in data often encountered in cultural heritage



This single object was part of a broader study of artists' workshop practice in 14th century Florence, focusing on the output of Pacino di Bonaguida. More than 30 objects were studied, using a variety of different techniques. Even though all the work was performed by GCI researchers, because some of the work was done "on the road" with portable instrumentation, the type and amount of data varied considerably across the study. Although differences inevitably occurred in both the types and depth of the analyses that could be performed on each object in the study group, taken together, the large number of works investigated provides greater statistical relevance than could be gleaned from the study of any single object.

http://www.getty.edu/conservation/our_projects/science/florentine/index.html
Florence at the Dawn of the Renaissance: Painting and Illumination 1300-1350. Ed. Christine Sciacca. 2012. Los Angeles: The J. Paul Getty Museum.

Contributed by Catherine Patterson and Karen Trentelman

Closer to Van Eyck: Rediscovering the Ghent Altarpiece

In 2010, van Eyck's renowned Ghent Altarpiece was temporarily dismantled and examined within St. Bavo Cathedral to determine whether a full restoration treatment of the polyptych was required. This examination, supported by the Getty Foundation's Panel Painting Initiative, made it possible to undertake a technical documentation campaign with macro-photography in the visible, infrared reflectography (IRR), X-radiography, and dendrochronology. In addition, the central panels were documented with multispectral scanning and non-invasive instrumental analyses such as XRF, XRD, and UV-VIS spectroscopies. The resulting digital archive of research reports and high- and extreme-resolution images provides truly unique material for anyone who wishes to study the intensely-detailed Ghent Altarpiece, van Eyck's painting technique, or the conservation history of the altarpiece.

To make all these materials readily accessible for a larger audience, as well as for specialist art historians and art conservators, a web application was created to view, study, and compare these images in full resolution. Images were stitched into new, very large composite images and co-registered, allowing for unprecedented close scrutiny and comparative study. An innovative use of social media enables scholars as well as Facebook users to easily communicate about specific details or comparisons. The site has rapidly become a popular teaching resource in academia as well as an indispensible work tool for the team of that is currently restoring the Ghent Altarpiece. The research and conservation reports from 2010 are made available as well, in addition to images of cleaning tests and short educational texts about the methods of documentation. In the coming years, keeping pace with the cleaning of the Ghent Altarpiece, which is scheduled to be completed in 2017, the application will be augmented with images during and after treatment, educational videos, and treatment reports.

http://closertovaneyck.kikirpa.be
Contributed by Ron Spronk

Discussion Theme I: New avenues of research that will be made possible by the integration of analytical, imaging observational data

In this, the first of the four main discussion themes, the participants began to explore what new avenues of research might be made possible through data integration, and why this would be valuable. Jim Coddington (MoMA) introduced the topic. To stimulate discussion, Jim suggested that new research in cultural heritage might also include applying new, more precise tools to old efforts, or adapting research protocols from other disciplines (e.g. GIS platforms, network frameworks). He also asked the participants to consider what adaptations/concessions would need to be made to make these protocols useful for cultural heritage work. The participants were asked to identify the current and predictable upcoming needs of researchers that might benefit from data integration, and the challenges that will need to be overcome.

Several types of research programs were identified as particular beneficiaries of better data integration, falling into the broad categories of advancing technical studies of artifacts, advancing conservation practice, or improving the ability to mine and share data. Some linkages between these types of research programs were also identified, such as the expected improved ability to generate data-based models of the objects examined. Several areas for development were also suggested, in order to address the challenges participants identified. Major areas for research/development include metadata management, software architecture frameworks, and structures for ongoing support/governance of integrated data platforms.

The desired new research capabilities provided by data integration:

- Advancing technical studies (attribution/provenance/technology):
  - Link materials to time/location/artist's methods;
  - Determine classification and degree of similarity of objects via multiple measurements;
  - Automated image/facial recognition;
  - Machine learning to define characteristics;
  - Create models to confirm experimental data to determine materials/methods of construction.

- Advancing conservation practice:
  - Provide timely data feedback for environmental monitoring (e.g. embedded sensors) or conservation treatment questions (e.g. potsherd re-assembly);
  - Uncover relationships between material properties and behavior (e.g. craquelure to stratigraphy, thread count);
  - Use image/text mining of historic records to look for trends in degradation (e.g. cracks, fading, corrosion);

- Advanced modeling to predict future behavior (e.g. color change over very long times);
    - Ability to create virtual reconstructions/visualizations informed by data;
    - Automated image comparison for condition reporting.
- Mining and sharing data:
    - Allow data from different techniques/different researchers to be linked both to each other and to specific locations for search/query (e.g. allow user to select region of interest and access all conservation, curatorial and scientific data relating to that location);
    - Allow text mining of published literature and/or metadata to determine current research trends and develop "tool kit" for ongoing research (including meta-analysis), and develop relevant ontology;
    - Allow generalization of sampling results across broader area, so as to limit/fine tune sampling campaigns;
    - Provide ability to do remote consulting/collaborating; ability to improve the efficiency of data interpretation (by individuals or collaborating groups) through iteration;
    - Facilitate truly interdisciplinary, collaborative work; extension to adjacent disciplines will increase "out of the box" thinking; encourage data sharing; valuation of data/peer review achieved through "hit" rate/wiki-type model.

Resources that may need to be developed to achieve these research goals:

- General
    - Look to other disciplines (e.g. medicine, astronomy, finance) for examples and starting points; encourage connections to non-traditional partner fields;
    - Take advantage of resources already developed (e.g. schema.org);
    - Incorporate integration into workflow;
    - Establish mechanisms to evaluate quality/reputation and the provenance of data.

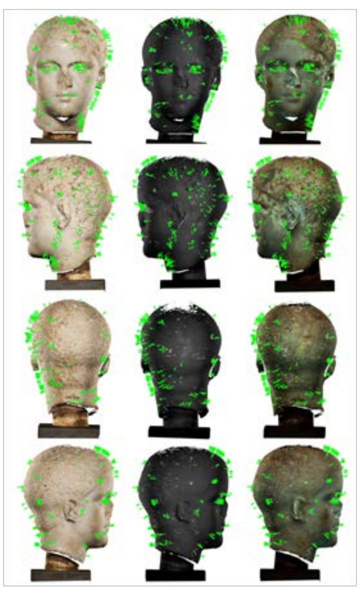
- Metadata
    - Develop standards for metadata, vocabularies and relevant ontologies;
    - Facilitate automatic collection of entering metadata, or incentivize manual entry;
    - Create unique identifiers to be attached to all digital "objects" (which includes all data, metadata, images, etc.).

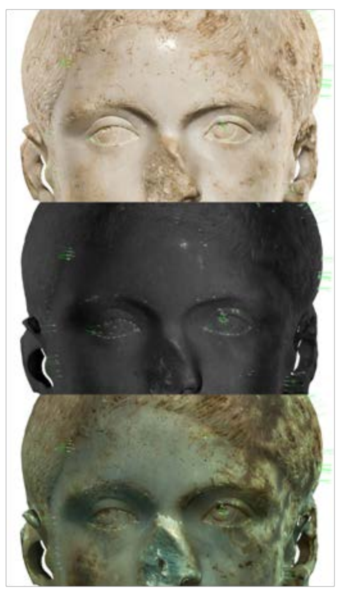
- Software architecture
  - Develop real-time visual interface/browser and customized interface for cultural heritage;
  - Develop IT research (rather than support) partners;
  - Use semantics/semantic web standards to insure data/metadata remains accessible, searchable, and interpretable;
  - Incorporate machine learning mechanisms to provide iterative advancement.
- Support/governance
  - Identify appropriate financial support for development and maintenance (including data storage and platform maintenance);
  - Engage computer science/information studies/data visualization professionals;
  - Establish policies for data sharing (e.g. period of proprietary ownership before sharing, author credits, privacy issues).

3D Models as Integrated Data Platforms

The adoption of digital methods of documentation and use of 3D models in research impel discovery and cultivate the synthesis of new knowledge with implications for museum collections conservation, research and education. 3D models can be employed as active agents of investigation, upon which interdisciplinary data may be projected and with which scientists and the public may interact virtually in a host of otherwise impossible manners. This case study[1] illustrates how 3D models can serve as integrated platforms for visualization of data and extrapolation of information.

The main objective of the case study was to create a three-dimensional platform for exploration, comparison and visualization of data related to polychromy studies. A 3D model of the surface geometry of the portrait was created from points captured via triangulation laser scanner. First, the model was commissioned to give dimension to data. Contemporary color information and technical imagery were texture mapped onto the model. Pigment traces (documented on 2D images) were mapped onto the 3D model and thus given spatial context. The model stands as a point of confluence for the 3D map of pigment traces and texture maps of technical imagery to be viewed in conjunction. Color information can be turned off and on to explore the relationship between surface geometry, pigment traces and luminous phenomena to bring more understanding to tool marks, painting methods, positions and interactions of pigments, as well as the relationship between the work of the sculptor and the painter.





Second, the model was meant to stand as a digital replica for speculation on the relationships between data and experimentation with the interplay and layering of pigments. Color was restored to the portrait through a digital color interpretation on the 3D model. Colors corresponding to pigments from antiquity were painted over the contemporary color information of the portrait to varying degrees of translucency. Digital methods lent the ability to create a 3D platform to document and amass data, as well as visualize, interact with and interpret it in innovative ways.

[1] *Cf. Tracking Colour. Preliminary report 4, 2011, 64-88, at http://www.glyptoteket.dk/sites/default/files/trackingcolour-4.pdf*

Contributed by Chelsea Alene Graham

Discussion Themes IIa and IIb: Most promising data/software types for first-generation integrated platforms

Building upon the previous discussion, the participants were next asked to identify the most promising data types and software technologies for integration. Giacomo Chiari (GCI) introduced the topic by giving a few examples of how multiple data types taken together are typically necessary in order to gain a fuller understanding of an artist, object or conservation issue. Curtis Wong (Microsoft) and Robert Stein (Dallas Museum of Art) provided examples of successful data integration/visualization from their respective work as examples to stimulate discussion. The participants were asked to identify the data types and software resources that were most promising for developing first-generation integrated data platforms.

Several different categories of data (images/spectra/text and recent/historic) were discussed, with specific examples provided for each category. Additional information types identified as being important for new integration platforms that leverage existing work both within, and external to, the cultural heritage research community (such as GIS information and existing databases) were also identified. Several specific existing software resources/tools that may be incorporated into an integrated data platform were noted by participants. Additional areas likely to need further development, both software tools and human resources, were also identified.

The most promising/important data types identified for integration included:

- Images:
  - Primary image of objects should be selected to serve as a starting point/framework for integrating the other data types;
  - Important image types include: color, monochrome, stereoscopic, microscopic (with scalable scale markers), 3D tomography, RTI; typically recorded in a digital image file format (e.g. jpg, TIFF);
  - Images may also include chemical data - image cubes/maps;
  - Images may also include associated metadata (recorded as text).

- Spectra:
  - All types of spectra (record of physical response as a function of a continuous variable, such as wavelength, energy, mass/charge, diffraction angle); typically presented as table of x,y data, or as a graph;
  - Standards for normalizing/scaling spectra, and relative sensitivity of measurement, should be included to facilitate comparison of linked data.

- Text:
  - Includes metadata, experimental/field notes, curatorial observations, publications, reports, labels, annotations (i.e. associated information, such as artist's name, date, etc);
  - May need to be translated to common language, with shared ontology.
- Other data/inputs:
  - Existing databases (particularly those already developed for cultural heritage);
  - GIS/geotagging data;
  - Results of statistical analyses.

The most promising/important software resources identified to support integration included:

- Better utilization of existing resources:
  - Public resources (e.g. search engines, semantic markup tools (e.g. schema.org), public data);
  - Data visualization tools for interactive access (e.g. Tableau, Graphvis, D3, Viewshare);
  - Image processing tools (e.g. openCV, VIK, VIPS, ImageMagick); image overlay tools (with edge detection algorithms);
  - Text mining tools, including sentiment analysis, to determine relative importance of research trends;
  - Chemical analysis software;
  - Trending analysis;
  - Database technologies that support flexible data storage and access: graph databases (e.g. neo4j); nosql schema-less data bases (e.g. mongodb);
  - Version control software (e.g. GitHub);
  - GIS tools (proprietary, need custom projection to enable, but can query spatially and textually);
  - Open source software (but has problems with version management);
  - Software storage and exchange platforms and data standards (e.g. HDF5, AnIML/XML).
- Resources that need to be developed/considered:
  - Vocabulary/metadata standards;
  - System for standardization of queries; common shared management system or middleware that can address queries;

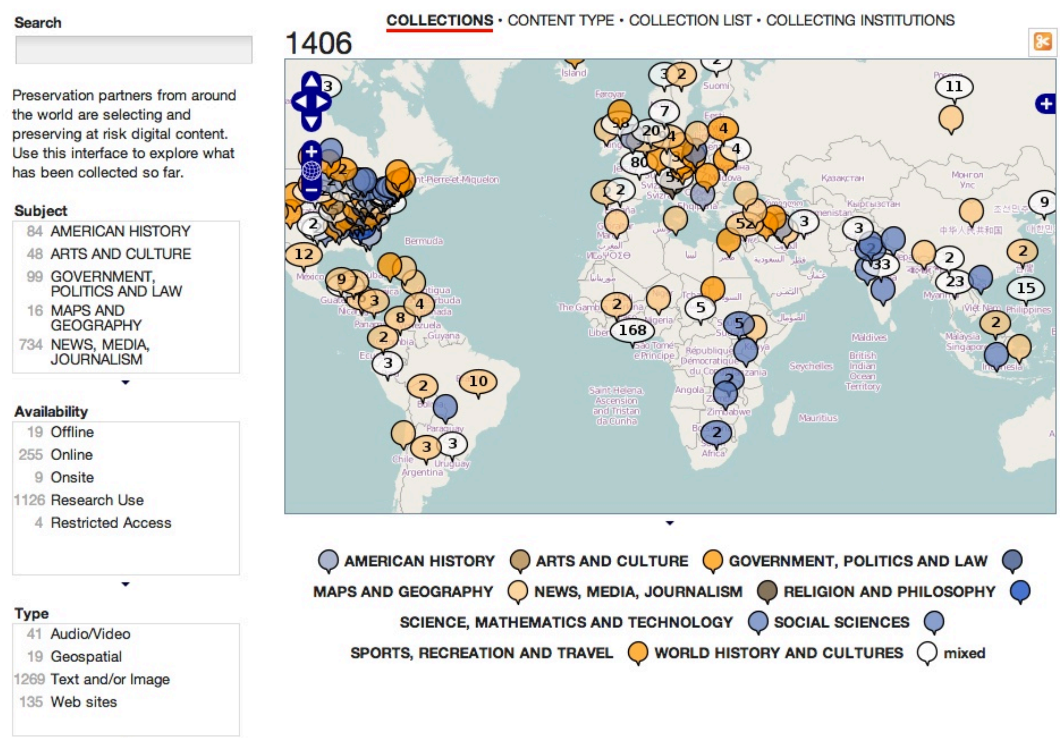
- Expertise in digital objects curation; enhanced IT resources;
- Expertise in cultural heritage within open source software community;
- Policies for data sharing, data ownership;
- Mechanism for social curation of data;
- User training (for a wide variety of user types involved in cultural heritage research, and for both students and professionals).

- Resources that could be implemented/developed relatively easily/quickly:
  - Automate registration/alignment of images;
  - Employ crowd sourcing to help with classification;
  - Develop image annotation tools;
  - Adapt GIS system for objects (with ortho-rectification and registration tools built-in);
  - Develop/adapt text-mining tools for cultural heritage;
  - Develop data audit trails.

Social Curation and Surfacing Patterns in Data

The National Digital Information Infrastructure and Preservation Program (NDIIPP) is an effort funded by the US Library of Congress to develop a national strategy to collect, archive and preserve the burgeoning amounts of digital content for current and future generations. It is based on an understanding that digital stewardship on a national scale depends on active cooperation between communities in public and private sectors.

The digital content created by these institutions grows in value exponentially as it is integrated and interconnected. The Library, in collaboration with Zepheira, LLC, has developed a platform called Viewshare to allow communities of interest to interconnect their information. Viewshare is a platform for generating and customizing views (interactive maps, timelines, facets, tag clouds) that allows users to experience digital collections. The platform uses semantic technologies to enhance discoverable access for NDIIPP collections, making them easier to find, access, analyze and share, and especially to integrate with other digital information sources. The Viewshare platform enables third-party applications developed by private or public organizations as well as interested individuals to support education, research, policy analysis and other completely unforeseen uses. Zepheira has developed the framework to identify, locate and reuse information in NDIIPP collections, and an open interface for third parties, to plug services and applications into that framework.



The Library has built a preservation network of over 180 partners from across the nation to tackle the challenge, and is working with them on a wide spectrum of initiatives including collections of historical, scientific, cartographical, media, legislative and sociological materials. Viewshare provides the Library and its partners a new paradigm for how their data are collected, stored, accessed, interpreted and shared among institutions and the users they serve.

http://viewshare.org/

Contributed by Eric Miller

Discussion Theme III: Implementation and adoption strategies for computer-assisted solutions to data integration

This discussion was the heart of the meeting, in which the participants were asked to develop the path to developing an integrated data system. John Delaney (National Gallery of Art, Washington) introduced the discussion by reviewing a few examples of (local) data integration, and proposing a software hierarchy to stimulate thinking and discussion. The participants were asked to identify the first steps towards adoption, looking for specific short- and long-term goals, and the challenges that would need to be overcome to achieve them.

The general consensus was that they best way to get started was to identify small pilot projects that could test the state of readiness of our data for integration and allow software developers to identify what tools/resources could be readily employed, and what needed further development. Rather than spending years developing protocols and standards before attempting implementation, it was agreed that it would be better to focus on a "minimum viable project (MVP)" to start quickly, and learn from any obstacles encountered to revise the process to achieve steady, iterative growth.

Suggested criteria for pilot project(s):

- Has well defined research goals that ensures work will add value;
- Has high visibility/importance for the field, with a possible public face (e.g. part of an exhibition), and wide geographic relevance;
- Is representative of a class of works of art (e.g. paintings, manuscripts, sculpture), and is expandable/extensible to other types of works beyond the original concept;
- Consists of a small (i.e. limited number of data types), but representative, collection of comparable data and data types;
- Is agile – the process will be inherently experimental, so the pilot project must be able to fail quickly, be revised and retested for iterative growth and ultimate success;
- Involves domain experts as well as end users.

Suggested criteria for software architecture:

- Basic, simple, modular structure that is expandable;
- Utilize a software stack (storage /access /research): different types of data and metadata are stored in individual repositories governed by a data catalog/registry (storage layer). This catalog/registry is accessed via a search engine, which communicates its findings to the user through a data browser to facilitate the discovery/selection of data sets (access layer). The selected data sets can be analyzed/visualized by the user through appropriate applications/tools (research layer);

- Need to create (i) unique identifiers for all assets/elements in the hierarchy, (ii) links between files and metadata, (iii) pointers/URLs to raw data, (iv) ontologies to link data to specific regions on images, and (v) shared control points between communities to assist navigation;

- Need to build (i) viewers for each data type, (ii) discovery tools to search for similarities between data, (iii) curation tool to allow "data checking" before uploading, (iv) specialized indexing and searching tools, and (v) image annotation tools.

Proposed activities to select/execute pilot project(s):

- Hold competition/call for data to select pilot project (selection to be made by review panel to be developed from meeting participants; possible first trial of social curation/decision making);

- Have groups of domain experts and/or hold round-robin to identify minimum/core metadata standards/vocabularies (and required domain-specific fields), and apply to project where data are about to be acquired;

- Utilize cooperative process for tool development – give pre-existing data from minimum of 3 institutions to group of software developers, perhaps with a "hack-a-thon" to test methodologies, evaluate robustness of currently existing data and metadata for integrating, sharing, searching and querying ("data dump");

- Test data sets from institutions with different institutional policies about data sharing to identify degree of openness necessary to build policy framework;

- Build links organically – begin with a "user study" and build towards desired experience in final environment.

Some general thoughts that emerged:

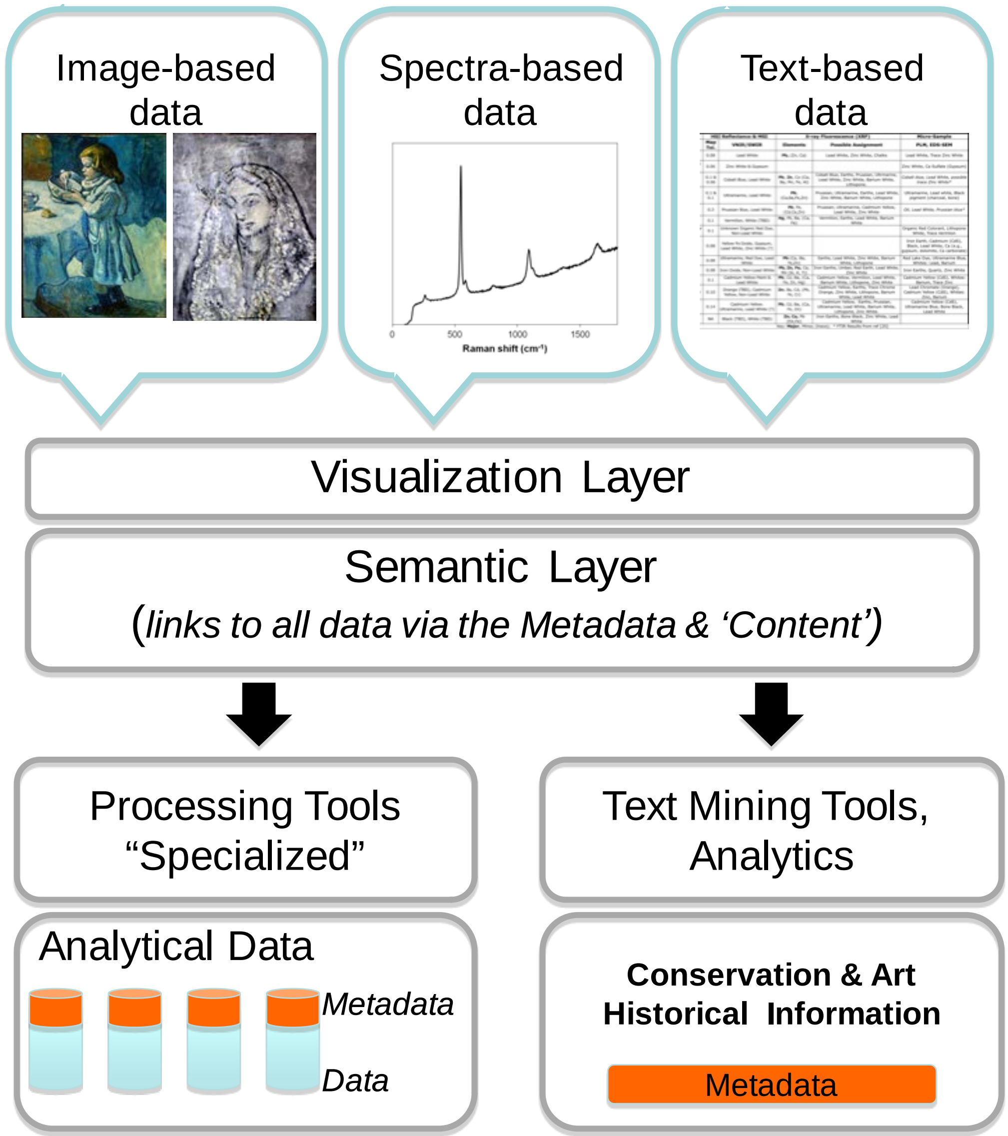
- The concept of a "region of interest" is very important – a user can define an area (of any size) on an object and retrieve all data relating to that area, which can alert researcher to additional related data and new questions;

- Any solution will have to be collaborative; success will depend on institutions becoming more open with their data and overcoming proprietary instincts; curation by collaboration can be effective, but will require a new paradigm of working;

- We should begin with most current data types to develop platform/protocols, and reserve digitizing legacy/historic until standards have been established;

- Integration can connect researchers to a larger context; begin with small group of researchers that progressively expands, with eventual connection to previously untapped (but possibly relevant) fields (e.g. botany, psychology, astronomy).

Basic Needs of Software Hierarchy for Integrating Cultural Heritage Data



A notional scheme describing the software architecture with key processing steps: specialized software viewer tools to allow users to explore primary images, analytical results as well as art historical papers, conservator's notes and information available on the internet. Low-level software tools to provide scientists and conservators the ability to analyze and make image and text reports obtained from both traditional images (e.g. X-ray, color, IRR) as well as advanced imaging methods such as macro reflectance imaging spectroscopy and XRF scanning. The key to tying the levels together is a semantic layer that allows the users to effectively search and organize the various data sets.

(Image: Picasso's Le Gourmet, 1901, Chester Dale Collection, NGA, DC)

Contributed by John Delaney and Ruven Pillay

Discussion Theme IV: Creation and continuity – users and developers

The final discussion of the meeting focused on the development of a working community to build and sustain data integration efforts. Ruven Pillay (C2RMF - Palais du Louvre) introduced the topic by mentioning some tools commonly used in other, similar, communities (e.g. websites, software sharing platforms), and asking the participants to discuss, for cultural heritage data integration, who should be involved, what community resources would be most valuable, what forms of communication should be employed, what education/dissemination activities would be most valuable, and what software sharing protocols would best foster collaboration and data sharing.

Participants identified several specific activities that would be necessary to establish a working community, including defining goals and milestones, and initiating several small working group discussions/pilot projects to lay the foundations of the initiative. A theme that ran throughout the discussion was the need for maintaining a breadth of expertise in an open, sharing environment to foster communication, collaboration, and innovation.

Seeding the community

- Invite a core group to participate, build organically by rewarding people for joining/participating, find low friction ways to contribute;
- Develop a roadmap, define goals/milestones (mission statement);
- Develop working groups to complete specific tasks:
    - Define metadata fields and standards,
    - Develop prototypes for new tools (e.g. image annotation, viewers),
    - Examine current/past efforts,
    - Leverage existing databases (e.g. IRUG);
- Conduct "clinical" trials with volunteers, pilot project(s) (see above for discussion of types/attributes of pilot projects);
- Initiate platform for open community model of contributing, evaluating, revising (e.g. GitHub, Google groups);
- Hire, or partner with, dedicated software developers to support early work;
- Secure institutional commitment from participants.

Maintaining the community

- Training:
    - Develop resources for on-going training (e.g. virtual brown bag presentations, how-to videos, workshops, round-robins);

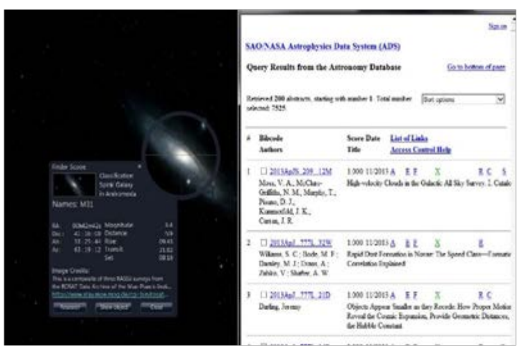
    - Establish centralized support group to maintain software and provide help/training so individuals could make contributions without the burden of having to supply continuing support;
    - Involve educators/educational organizations to teach new paradigm at early stages of career.
- Stewardship:
    - Establish steering/expert groups in different domains (e.g. conservation science , software development);
    - Identify "tastemakers" to be ambassadors for effort;
    - Identify and communicate with/through relevant professional organizations;
- Provide ongoing support for dedicated developers;
- Engage a broader range of communities by establishing a presence at conferences;
- Develop a marketing strategy (e.g. create a brand name, produce a white paper for participants to use when pitching effort to their institutions, develop a website to provide background and updates on progress).

Other general thoughts that emerged:

- Begin decentralized to foster innovation;
- Avoid creating artificial barriers to participation or unreasonable expectations;
- Avoid being overly cautious – start quickly, fail early, and revise often;
- Find ways to overcome institutional inertia and personal fears regarding sharing.

Integrating Image, Data and Annotation for Scientific Collaboration

The democratization of access to astronomy data began around the start of the millennium when skyserver.org made astronomical imagery and data from the Sloan Digital Sky Survey broadly available to the astronomical community. Other image and data sources came online in subsequent years, and international standards bodies developed metadata standards (AVM) to facilitate the integration of multispectral imagery with other data sources. By 2008, WorldWide Telescope (WWT) launched as an integrated image, data and annotation environment, bringing together (>100) multispectral all - sky surveys ranging in size from megapixels to terapixels, covering wavelengths from radio to visible to x-ray and gamma ray. The metadata standards allowed for all imagery to be registered to precise sky coordinates, allowing for cross-fading comparison of any two multispectral images at any level of zoom.



WWT presents wide field (60 degree) views of the night sky as well as seamless panning and zooming to a fraction of an arc second of resolution. Annotations (Guided Tours) that look like a movie can be easily created by capturing snapshots of objects or multispectral imagery at a selected zoom level. WWT weaves these waypoints into a seamless tour that can feature narration, text, graphics, animation, and related imagery on top of whatever background multispectral imagery is chosen. A key capability of a tour is that it can be paused at any time and the user is free to explore from that point; zooming in for more detail, choosing another multispectral view for context or using the Finder Scope for more information. Bringing up the Finder Scope allows the user to access to related scholarship, source imagery or data.

WWT's rich narration, exploration and access to source data can also be used for astronomy education and outreach. Tours have been created by people of all ages and education levels - from a tour of the Ring Nebula created by a 6 year-old to tours on star formation created by graduate astronomers. Organizations like the Adler planetarium have created full dome public shows with narration, music and full interactivity at any time for deeper audience engagement.

Guided Tours can serve both education and scientific research by looking like a video while retaining the benefits of full interactivity for re-annotation and sharing of collaborative insight about the observed issue being analyzed and evaluated. An in depth look at WWT could provide some useful ideas in the course of designing an integrated image, data and annotation environment for cultural heritage research and education.

http://www.worldwidetelescope.org
Contributed by Curtis Wong

Conclusions

Over the course of the Experts' Meeting it became clear that the contribution of scientific and technical studies to the conservation and understanding of works of art through the computer-assisted integration of imaging and analytical data could best be improved by changing the way we work to a more global community based on sharing data more freely. This would better enable integration of different types of data, from different researchers at different institutions that would facilitate broader, more meaningful and new types of research to be conducted. In short we should ***create a new paradigm for the way data are collected, stored, accessed, share, analyzed and interpreted.***

In this new paradigm, the integration of multiple types of data into a consistent, accurate, and useful, likely visual, representation, and the linking of data from several sources (i.e. researchers/institutions) is expected to facilitate comparisons/correlations between different objects, different studies, and over time. The linking of data from multiple sources will add value to each individual data source, and the building of communities of experts with an interest in the shared data will improve the quality of the interpretations made using the data. Taken together, then, such a paradigm will better leverage scientific and technical studies to advance cultural heritage research.

Though the integration of data, images, and observational data opens new avenues of research, it was noted that successful implementation of a new paradigm may require the concurrent development of a policy-aware infrastructure that can be utilized effectively even when the institutional policies of partners regarding sharing/openness of data (particularly initially) differ. Additionally, it may initially be difficult to manage/utilize the new connections made possible by an integrated data platform, and expectation management will be necessary for all participants.

This new paradigm will also require the development of a specialized data storage/access/ interpretation platform, which will be the portal through which data may be shared and better utilized. This platform may need to include several levels of access (i.e. access to collaborating groups vs. public access), and will need to be specific to the needs of the cultural heritage community. A number of existing software architectures and data/image analysis tools were identified during the meeting as potentially fruitful models or components for such a platform, though it is probable that some degree of adaptation may be required to make these tools appropriate for the data found in cultural heritage research.

It was determined that the most efficient way to create the needed data platform for cultural heritage research would be to initiate one or more pilot projects that begin to employ existing architectures/tools, determining the state of the field and appropriateness to cultural heritage materials/data. Several mechanisms for selection of pilot projects and criteria for those projects were outlined during the meeting.

In order to ensure the success of the pilot projects, it was determined that special focus should be paid to the development of standards for metadata to be captured/stored with data and/or images, taking advantage of existing standards from other fields where possible. Several mechanisms were outlined for determining the minimum metadata set that must be available for given data types, and for establishing a common ontology for cultural heritage data/images in order to facilitate relational building (or integration) between disparate data types.

Overall, the group identified several short- and long-term goals that should be achieved in order to advance the development of a new paradigm for the use of cultural heritage research data.

In the *short term*, common data formats, metadata standards and standard ontologies must be developed and implemented. An evaluation of past and related data collection/integration projects should be undertaken, and lessons that can be gleaned from past work identified. One or more pilot projects should be proposed, selected, and executed (related to e.g. specific artists or selected conservation issues). Such projects should be oriented to test the current state of the field, identify areas for further research and development, and determine requirements for institutional data collection and sharing policies. During the execution of the pilot projects, prototypes for new tools specific to the analysis of cultural heritage data will also be developed. The pilot projects should be relatively small but representative, agile, and flexible – they should start quickly, fail early, and be revised as necessary.

In the *longer term*, the lessons learned from the pilot projects will be used to help advise institutional sharing policies, and to begin to format legacy data (particularly non-digital) in such a way that it can be migrated onto the new platform(s). Each prototype platform will also be opened to larger-scale community contributions, and evaluations, and revised accordingly. As the platform is iterated, it is expected that larger, more complex 'beta' projects that test and expand its capabilities will be undertaken. As the platform matures, a centralized support structure can be developed, to ease adoption of the new research paradigm for institutions and individual researchers. Activities to broaden the community network will also be undertaken (e.g. conferences/workshops etc.), leveraging existing professional communities within the cultural heritage field, including the educational centers for conservation and conservation science.

As the questions raised in the field of cultural heritage research become ever more complex, a fuller understanding of the information collected by researchers is needed to improve the contribution of scientific and technical studies to the conservation and understanding of works of art. The frustration of having more data than can be effectively managed and understood is shared by many researchers. This meeting was therefore timely, bringing together experts in a variety of fields to determine the most efficacious means of integrating and mining the broad data sets typical of cultural heritage research, exploiting the depth and complexity of the data sets to generate new types of information, and providing mechanisms for asking – and answering – the next generation of research questions.

Appendix: Defining Terms and Concepts

Chromatographic techniques (gas chromatography (GC)/liquid chromatography (LC)/ion chromatography (IC)) – Chromatography is used (in several forms) in cultural heritage to separately identify components of complex mixed materials, typically organic in nature, or to determine the relative ratio of one component to another to help identify material sources.

Electron emission imaging – Imaging using the electrons emitted from the upper surface of an object during x-ray exposure. This technique can be helpful in determining the location of a material in a composite object with a complicated x-radiography image.

Fourier transform infrared (FTIR) spectroscopy – A molecular fingerprint spectroscopy in which vibrational signatures allow material identification through comparison to known or reported spectra, and which uses infrared light to initiate vibrational motion. The technique can be used to identify many material types, but is most often employed in the analysis of organic species.

Hyperspectral cube – More complicated images, such as hyperspectral images, are usually stored as uncompressed binary data in a "cube" combining image spatial data as well as spectral data per point.

IDL (interactive data language) – A data analysis programming language utilized by several scientific fields, including medicine and astronomy.

Image formats: FITS (flexible image transport system) – A standard format used for astronomical data that is designed to store both images and scientific data sets, including spectra, data cubes, and tabular data.

Image formats: TIFF, JPEG, JPEG2000 – TIFF and JPEG2000 are archival image formats capable of handling various bit-depths (8,16,32 bits), color spaces, and advanced features such as tiling and multi-resolution encoding. They can both be compressed both losslessly or lossily. For archival use, any compression should be lossless, where data can be perfectly reproduced after decompression. Lossy compression allows far greater compression and therefore smaller file sizes, but at the cost of some data loss. JPEG is a lossy compression format, which usually only handles 8 bit images and thus, is not generally used for archiving purposes.

Image fusion – The registration of images sets to each other often obtained by different imaging modalities which when 'processed' yields new information not obtainable from the analysis of the independent images sets.

Image metadata formats: EXIF, IPTC, XMP – These are image metadata formats used to store information such as image date, aperture settings, exposure etc. IPTC and XMP can also contain other user-defined meta-data.

Image registration – Images of the same object can be taken at different times, different viewpoints or under different conditions. Registration allows images to be precisely matched together such that each detail superimposes perfectly (based on control points determined by either a manual or automatic process) and can be compared. Registration can be complicated due to distortions resulting from the camera, lens or type of imaging.

Imaging spectroscopy (or hyperpsectral imaging) – Collection of calibrated images collected at a sufficient number of bands (wavelength (for reflectance), spectral radiance (for luminescence), energy (for XRF)) to provide a contiguous spectrum with spectral resolution similar to a bench-top single-point measurement.

Infrared reflectograpy – Monochrome (black and white) imaging of polychrome art work in regions of the near infrared (750 to 2500 nm), which can penetrate the painted surface to reveal preparatory sketches and compositional changes. Single band image products are called infrared reflectograms.

Mass spectrometry techniques – Several mass spectrometric techniques are utilized in cultural heritage research, sometimes combined with chromatographic techniques (e.g. GC-MS, Py-GC-MS, LC-MS), and other times standing alone (LA-ICP-MS, MALDI). Each technique is utilized to both qualitatively identify, and in many cases quantify, materials found in low concentrations due to the sensitivity of mass spectrometric techniques. These techniques are used for the analysis of both organic and inorganic materials.

Multi-band imaging – Collection of a few to ~100's of images in the same or different image modalities.

Multispectral imaging – Collection of images in from a few to ~100 spectral bands, which may not be contiguous; produces an approximate spectrum compared to a bench top instrument.

Open source software – Open source software is software whose source code is available to the user and that can be copied, modified and redistributed subject to certain copyright and licensing restrictions. This allows software to be made available for free and for anyone to collaborate and help improve it. Much of the core infrastructure of the web is open source, as are a number of desktop applications such as Firefox and Thunderbird. The most widely used license is the GPL, which allows copying, modification and redistribution as long as the software is redistributed under the same terms. Other more permissive licenses allow unrestricted re-use as long as the original author is credited.

Photomicroscopy – Imaging, typically in visible light, done of a magnified portion of an object to show features not clearly visible to the naked eye.

Physical measurements – A wide variety of physical measurement techniques are utilized in conservation science, including (but not limited to) measurements of hardness, strength, color, fading/light sensitivity, dynamic mechanical analysis (DMA, for measuring viscoelasticity), and porosity.

Raking light photography – Imaging that employs use of a strong light across the surface of an object to highlight surface textural patterns, such as brush strokes.

Raman spectroscopy – A molecular fingerprint spectroscopy in which vibrational signatures allow material identification through comparison to known or reported spectra, and which uses laser light to initiate Raman scattering. The technique can be used to identify many materials based on the laser line chosen, but is most often employed in the analysis of inorganic species.

Reflectance Transformation Imaging (RTI)/Polynomial Texture Mapping (PTM) – Interactive versions of raking light photography that allow the point light source to be digitally manipulated by combining a sequence of images taken under varying conditions.

Scanning electron microscopy - energy dispersive x-ray spectroscopy (SEM-EDS) – SEM-EDS is a non-destructive technique conducted in a low vacuum which provides both images reflecting variations in atomic number/density within the sample, and elemental data for discrete areas/particles in a sample. This technique is particularly useful in the analysis of cross-sections.

Scanning electron microscopy (SEM)/transmission electron microscopy (TEM) – SEM and TEM are non-destructive techniques conducted via electron bombardment under vacuum, and provide images reflecting variations in atomic number/density within a sample at magnifications much higher than can be achieved using visible light.

Spectrophotometry/fiber optic reflectance spectroscopy (FORS) – Reflection spectrophotometry and fiber optic reflectance spectroscopy measure the relative absorbance/reflectance of various wavelengths of light and may be used either to objectively measure color, or for material identification.

UV (excitation) imaging – Color photography of polychrome art objects illuminated with UV light, often used to identify/locate areas of overpaint or organic materials. Filters block the UV excitation to allow capture of the luminescence and or fluorescence emitted by the varnishes, pigments and paint binders present. Since the cameras are un-calibrated the color appearance is subjective and often 'tweaked' to better match the visible appearance of the painting under the UV lamps.

UV reflectance imaging – Imaging art objects in the UV (300 to 400 nm), often used to separate pigments such as lead, zinc and titanium whites

Web-based vs desktop software – Desktop software is software designed to run locally on your computer and, therefore, requires adaptation for various platform (Windows, Mac, Linux, Android, iOS). Web-based software uses web standards to run within any web navigator, making it easier to distribute and more portable. However, performance will be inferior compared to dedicated desktop software.

Web technologies: HTML5, CSS3, WebGL – Advances in web standards and technologies have made it possible to create sophisticated software that can run directly within a browser on any operating system, as well as on mobile devices. Such web apps make it simple to access advanced services, but are dependent on networked server-based services.

X-radiography – Imaging using x-rays, which can be used to examine objects ranging from works on paper (done at energies <10 kV to image water-marks), to paintings (typically done at 30 to 60 kV), to objects such as sculpture or furniture (typically imaged at higher kV because of the higher x-ray opacity).

X-ray absorption spectroscopies (Extended X-ray Absorption Fine Structure (EXAFS)/X-ray absorption near edge structure (XANES)) – X-ray based techniques, typically using a synchrotron radiation source, which help identify elements in a sample and determine their oxidation state and coordination chemistry. The techniques are usually utilized for detailed material and mechanistic analysis.

X-ray diffraction (XRD) – A molecular analysis technique that utilizes the scattering of x-rays from a crystal structure to determine the structure and bonding environment of a material. The technique is particularly helpful in identifying the crystalline mineral components of a sample.

X-ray fluorescence (XRF) spectroscopy – A non-destructive x-ray-based technique which is used to identify the elemental composition of discrete areas, and which can detect the majority of elements commonly found in mineral-based pigments.

X-ray photoelectron spectroscopy (XPS) – An electron spectroscopy that provides atomic composition, oxidation state, and structural information about a sample.

XML, JSON – XML and JSON are standard data interchange formats often used for web-based data exchange and are often used when web applications communicate with the server.

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