Making Light Work: Manuscripts and Multispectral Imaging

HELEN DAVIES AND ALEXANDER J. ZAWACKI

The Technology

Multispectral imaging (MSI)—a form of digital photography that captures images across a portion of the electromagnetic spectrum wider than the visible—is a nondestructive technology capable of recovering text and images from cultural heritage objects that have been faded, stained, charred, used as palimpsests, stained, or otherwise rendered obscure or illegible. Its abilities in this capacity vastly outstrip traditional methods (e.g., ultraviolet or infrared photography), because it allows the selective combination of images taken at various wavelengths of light, which are ideally suited to statistical processing methods. A small but growing number of teams, highly collaborative in nature, have worked with collections across the world to exploit the potential of MSI to enrich our store of cultural knowledge by digitally restoring objects.

The present article offers a brief overview of the technology in its current state, followed by a short history of major projects in the field; that is, some of those that have produced sizeable book publications, digital archives, or both. It makes no claim to being exhaustive; rather, it seeks to serve as an introduction to the field for those unacquainted with it. It is hoped that this will provide the broader scholarly community a somewhat fuller picture of what items and collections have been imaged, what results were achieved, and what remains to be done.

A modern MSI setup consists of several components: camera, lens, copy stand and cradle, and lights. The camera and lights (and, if mechanized, the stand as well) are controlled via computer. Systems built by MegaVision, Inc. use the proprietary program Photoshoot, which allows for image calibration, the production of high-fidelity color images, and the export of images in multiple formats. MSI setups employing Phase One cameras may use Capture One, which allows for both camera control and image editing.

Within the camera lies a monochrome sensor that offers numerous advantages over cameras with color sensors. To begin with, because the object is photographed in only one wavelength of light at a time, a color sensor is simply unnecessary. More importantly, monochrome cameras are capable of capturing images with significantly higher resolution than color cameras and display greater light sensitivity.

Lenses are crucial to the quality of all the data captured. Whereas nearly all modern (achromatic) lenses are designed to deliver focus across the visible spectrum, MSI requires a so-called apochromatic lens that remains focused in both the UV and IR wavelengths. Such lenses allow for significantly improved focus in the ultraviolet and infrared wavelengths and decrease the effects of spherical and chromatic aberration. Unlike off-the-shelf lenses, an apochromatic lens for MSI should also be transparent to UV light.

The copy stand holds the camera parallel to the focal plane and allows for height adjustment. Depending on the size and type of object being imaged, the copy stand may take various forms and orientations. Manuscripts, for example, are generally imaged either directly from above or with the copy stand and manuscript on a slightly tilted stage to reduce stress on the binding. Large, flat objects, such as maps or paintings, are best imaged upright on an x-y easel, requiring that the lights and camera be mounted on a robust tripod. The design of the book cradle is also essential to safe material handling. This component can take various forms according to the preferences of the team and the project: a manuscript, for example, will require a significantly different type of stand from a globe. Michael Phelps and his team at EMEL have, with Stokes Imaging, developed a cutting-edge book cradle with computer-controlled motors that rotate the spine of the manuscript as the pages are turned. This accommodates the shifting weight of the codex and alleviates strain on the binding while maintaining a constant focal plane; thus the camera operator is not obliged to refocus the camera in order to compensate for the movement page by page through the manuscript.

Lights are placed on either side of the stand as in traditional imaging. Specific light configurations and wavelengths can vary by team and by project, but the most advanced systems employ light-emitting diodes (LEDs) capable of illuminating from the ultraviolet through the visible portions of the spectrum and into the infrared. The Lazarus Project, an MSI team at the University of Rochester of which both authors of the present article are members, places the main banks of lights behind diffuser screens at 45-degree angles to the object. These banks emit sixteen discrete wavelengths of light, from 365 nanometers

(nm) in the ultraviolet to 940 nm in the infrared. Banks of auxiliary lights sit below the main one and provide illumination at 365, 385, 400, and 450 nm.

Both the media—inks and pigments—and substrates—parchment, paper—reveal discrete features under each wavelength. The short waves of ultraviolet light, for example, are particularly well suited to provoking fluorescence—the absorption of light by an object at a shorter wavelength and its reemission at a longer wavelength. The mildly fluorescent properties of parchment may be further exploited by placing in front of the lens a filter wheel that is capable of filtering out the UV light to which an object is exposed from the longer-wavelength light that the object is itself emitting.

Additionally, the team may opt to employ a transmissive light source, a thin sheet of acrylic placed under the object that shines light upwards in a series of wavelengths through the object and into the camera. Even if no ink remains on the object, the corrosive effect of iron gall ink thins the parchment where the letters had been; light will shine more brightly through these "ghost letters" than through the parchment around them, making the text legible once more.

Teams may further choose to employ raking light, a light source placed at an oblique angle of roughly 15 degrees to the object, casting minute textural features (raised or depressed) into sharp relief. In situations in which texture is particularly important (e.g., manuscripts that are badly cockled or that bear drypoint markings), a further process known as reflectance transformation imaging (RTI) may be used. Developed by research scientists at Hewlett-Packard Laboratories, RTI (known also as polynomial texture mapping) is performed by capturing a series of images of the object while illuminating it from discrete angles. These images are subsequently processed using a program that converts them into a single image and computes all possible angles of illumination within a hemisphere around the camera. The result is an interactive digital image across which a user can move a dynamically simulated light source in order to reveal surface features, color, and texture.

However, the real work of MSI lies less in capturing the images than in processing them. Only very rarely does any single raw image reveal everything from a given object that a scholar might wish to know. Portions of the text too faded or too thoroughly scraped away invariably remain. Statistical processing, albeit a labor-intensive task, often proves transformative for the worst-damaged objects. As of yet, no single computer program geared specifically toward processing multispectral images of cultural heritage objects exists. Scholars in the field have thus availed themselves of a small host of applications, many of which were designed originally to handle aerial and satellite imagery. ImageJ is an open-source, Java-based application developed by the National Institute of Health that is capable of processing multispectral images. William Christens-Barry, of Equipoise Imaging, LLC, has developed Paleo, a toolbox for ImageJ specifically designed for processing multispectral imaging. Open source and freely available code for the programming language and computing environment, MATLAB, enables it to perform a variety of statistical processing on images including principal component analysis (PCA) and independent component analysis (ICA), provided the scholar is proficient in its language. Another commonly used option is ENVI (ENvironment for Visualizing Images), developed by Harris Geospatial Solutions. Designed originally for the field of remote sensing with satellite and aerial imagery in mind, ENVI offers a suite of tools for MSI processing.

Some common statistical processing techniques include PCA, which attempts to reduce the image dataset to one in which the main features, or the principal components, are maximally uncorrelated (that is, most distinct from one another). ICA is a roughly similar process that looks for hidden factors underlying a set of signals by reducing a complex dataset to its independent subparts. Blur and divide (BAD) divides the image by a blurred version of itself in order to enhance contrast and sharpness, and spectral angle mapping (SAM) assesses the similarity between a set of target pixels and every other pixel of which the image is composed. Images may also be batch-processed, which automates some basic algorithms with the goal of amplifying the signal (e.g., the undertext) while minimizing the noise (e.g., the overtext). Finally, Adobe Photoshop or similar software (e.g., the open source application GIMP) may be used for some postprocessing tweaks: enhancing contrast, converting to black and white, adjusting hue, and so forth.

Each team, and often each individual scholar, has its own idiosyncratic methods of getting the best results from the MSI data in its program of choice. The field's youth, coupled with the geographic and institutional dispersal of the various teams, means that standard procedures and best practices have not yet been universally established. Imaging scientists and scholars frequently develop their own image processing techniques to deal with new circumstances or challenges, techniques that may then be shared among the community.

Some Major Projects

THE ARCHIMEDES PALIMPSEST

The history of digital MSI's application to cultural heritage objects begins in the first decade of the twenty-first century with the Archimedes Palimpsest. In 1906, philologist Johan Ludvig Heiberg realized that beneath the text of a thirteenth-century Byzantine Euchologion lay a copy of writings by Archimedes once thought to be lost. Heiberg transcribed much of this *scriptio inferior* (the erased undertext), but much more remained too faint

to be legible. When the manuscript went for auction in 1998 at Christie's in London, an anonymous American collector acquired it for two million dollars and subsequently lent it to the Walters Art Museum (then Gallery) in Baltimore for exhibition, conservation and study. There, William Noel led the team responsible for its care, while Abigail Quandt oversaw its conservation. A number of imaging scientists were eventually engaged under project manager Michael B. Toth. These included Roger Easton, Jr., Robert Johnston, and Keith Knox, as well as a second team led by William A. Christens-Barry.

Knox first developed the pseudocolor technique that has since become standard practice in the field and which combines various bands to produce a false color image in which targeted features (e.g., the undertext) are more sharply contrasted. Early imaging efforts were somewhat limited by contemporary technology, however, as the first systems employed relied upon the broadband illumination method described above. This method was supplanted in 2004 by a method developed by Christens-Barry: the use of narrowband LED light sources to illuminate the palimpsest with discrete wavelengths. The "final and complete" imaging was carried out in 2007 by Stokes Imaging, which employed a high-resolution camera capable of photographing entire leaves. Each folio was photographed in sixteen bands. The project has generated numerous publications and presentations, culminating (at least for the moment) in a two-volume commentary and (multispectral) image and transcription set.

THE SAN LORENZO PALIMPSEST

In its current incarnation, the San Lorenzo Palimpsest (Florence, Archivio del Capitolo di San Lorenzo MS. 2211) is a real-estate census for the church of San Lorenzo in Florence that chronicles the acquisitions, rentals, and maintenance of church properties. Bearing multiple erasures and additions, the record reaches "some kind of terminus" around 1504 but continued to be added to and revised until the mid-seventeenth century. In a past life, however, the folia on which this ongoing census is recorded belonged to an anthology of secular polyphony from the late 1410s, probably recorded by a single hand.

First recognized in 1984 by Frank D'Accone as a musical palimpsest, the manuscript now serves as a study in miniature of evolving imaging and cultural heritage recovery technologies. After D'Accone's pioneering discovery, the leaves were studied "using hand-held lenses with UV lighting at the Biblioteca Medicea Laurenziana." In 2001, high-resolution digital images of the manuscript were captured in Florence by the Digital Image Archive of Medieval Music (DIAMM) of the University of Oxford. These images were not multispectral and were taken before the advent of the statistical methods pioneered by the Archimedes team; thus processing was limited to the use of Adobe Photoshop in order to increase the legibility of the undertext.

The biggest break in the case, however, was the multispectral imaging project carried out at the Archivio del Capitolo of San Lorenzo by the University of Hamburg's Centre for the Study of Manuscript Cultures (CSMC) in June 2013. Unlike Archimedes, the San Lorenzo manuscript was not disbound, necessitating the construction of a specialized cradle to hold the manuscript during imaging. Multispectral imaging technology had advanced in the interim between the two projects; whereas Archimedes was imaged in sixteen bands, this was photographed in twenty-four. But the protocols originally devised during the Archimedes project for processing the images remained largely in place: scholars working on the San Lorenzo data used ENVI's PCA and ICA capabilities to produce pseudocolor images meant to maximize the contrast between the overtext and undertext. The result has been the recovery of an immensely rich anthology of secular music from the Florentine quattrocento, some 226 works altogether.

THE SINAI PALIMPSEST PROJECT

Whereas the two projects above focused on a single, uniquely important manuscript, the Sinai Palimpsest Project, based in St. Catherine's Monastery in Egypt, is remarkable for being much broader in scope. Since 2011, the Early Manuscripts Electronic Library (EMEL) has led the effort to apply MSI to all of the 160 known palimpsests at the monastery's library. An independent, nonprofit research organization, EMEL is directed by Michael Phelps. Previous projects have included work on a number of palimpsests at the Austrian National Library and the David Livingstone Diaries at UCLA, as well as a National Endowment for the Humanities–funded initiative aimed at more firmly integrating MSI and RTI technology.

To date, the project has successfully imaged 6,800 folios from seventy-four manuscripts, leading to the discovery and recovery of some 285 erased texts through the labors of twenty-three scholars. Notable texts recovered during multispectral imaging include a sixth-century copy of Hippocrates (the oldest surviving accredited recipe) and texts in the lost Caucasian Albanian language. EMEL works with the University of California, Los Angeles (UCLA) to make both true-color and multispectral images from Sinai Palimpsests Project freely available on the Web with an innovative viewer.A researcher may access all of these images through Mirador, which allows for flexible, easy access to high-resolution images and provides the capability for multiple synchronized workspaces to examine and compare manuscripts. Scholars can layer images (e.g., true color, pseudocolor), adjust

transparency and opacity, and easily access metadata (e.g., information on the codicology, overtext, and undertexts). All of the images are compliant with the International Image Interoperability Framework (IIIF). The Sinai Palimpsest Project may thus point out the route for future publications of MSI data: beyond static archives to interactive, dynamic data visualizations.

THE MARTELLUS MAP

The Martellus map (Art Store 1980.157) currently hangs in the Beinecke Rare Book and Manuscript Library at Yale University. Dating from the fifteenth century and measuring 4 feet by 6.5 feet, the map shows the world as Christopher Columbus understood it. It is likely that he consulted this map or one similar to it before his famous voyage to the Americas. Furthermore, it seems to have served as the basis for two later important cartographic representations: the 1492 Behaim globe and the 1507 Waldseemüller world map (the first to use the name America). The Lazarus Project and EMEL imaged the Martellus map, now etiolated and illegible, in 2014 in collaboration with Ken Boydston of MegaVision and Roger Easton, Jr., of Rochester Institute of Technology.

The sheer size of the Martellus map posed a significant obstacle to imaging efforts, necessitating the construction of a motorized easel on which the map was placed. This easel moved along an x-y axis to capture fifty-five image tiles (each 8176 x 6132 pixels) while the camera and the lights remained in a fixed position. Easton and Boydston, with Kevin Sacca, processed the majority of the images. Easton and Van Duzer developed a dynamic workflow in which Easton would send Van Duzer processed images, Van Duzer would highlight areas that required further processing, and Easton would direct additional efforts at those regions. As Van Duzer demonstrates, the new images permit in-depth study of the map for the first time in the modern era, leading to the discovery of many new geographical features and textual inscriptions. Van Duzer has a published a book-length study on the results and included the processed images as an electronic supplement.

Thus there exist many possible ways of presenting the results of an MSI project: the images might be published as a facsimile alone, as with San Lorenzo, or alongside a transcription, as with Archimedes, and/or made available online, either in a simple database form, as with Archimedes and the Syriac Galen Palimpsest, incorporated into a dynamic viewing apparatus, as with the St. Catherine's palimpsest, or as an electronic supplement to a printed book, as with Martellus. Alternatively, the images may not be published at all and instead may be used as the basis for a full critical edition of the text under consideration. Projects may focus on individual objects or on entire collections, on maps or manuscripts bound or disbound, and the approaches to these objects may be as varied as the objects themselves and as the research interests of the scholars investigating them.

All projects demand a significant investment of time and effort—not merely in the initial imaging of the object but throughout the (often quite lengthy) subsequent phase of processing and reprocessing the images thereby acquired until maximum legibility and maximum recovery are achieved. The potential funding requirements are, therefore, not inconsequential. Neither, however, are the potential fruits of such labor. MSI and adjacent technologies offer scholars the tantalizing possibility of adding new (old) texts, new (old) works, to the standing corpus of our shared cultural heritage. Physically these texts may be anything from a palimpsest in a desert monastery to a stained scrap of binder's waste in a private collection, but all are potentially within our reach.

University of Rochester

NOTES

1. Much of this focuses upon MSI's ability to recover once-lost text and images, but the technology has a wide array of applications, including conservation. See Christian Fischer and Ioanna Kakoulli, "Multispectral and Hyperspectral Imaging Technologies in Conservation: Current Research and Potential Applications," supplement, *Studies in Conservation* 51.S1 (2006):3–16; and M. B. Toth, "Developing Spectral Imaging: A Standardised Tool for Collaborative Conservation Support," *Proceedings of Care and Conservation of Manuscripts* 16 (2018):302–322. Scholars continue to push the boundaries of MSI's capabilities within the field of cultural heritage studies. One team, for example, has recently explored the potential for MSI (among other tools) to nondestructively read text written on scraps of papyrus within mummy cartonnage. See Adam Gibson, et al., "An Assessment of Multimodal Imaging of Subsurface Text in Mummy Cartonnage Using Surrogate Papyrus Phantoms," *Heritage Science* 6.1 (2018):7. Although many of the cultural heritage objects discussed below are Western in provenance, fascinating work has been and is being done on non-European manuscripts—see, e.g., Orna Almogi, Martin Delhey, Claire MacDonald, and Boryana Pouvkova, "Recovering Lost Writing and Beyond: Multispectral Imaging for Text-Related and Codicological Studies of Tibetan Paper and Sanskrit and Sanskrit Palm-Leaf Manuscripts," *Journal of the International Association of Buddhist Studies* 36.1–2 (2015):153–192. In addition, some brief mention ought to be made of the distinct technology of hyperspectral imaging (HSI), which employs a very different form of image-capture technology from the one described below. The most glaring difference between the two is the number of bands in which the object is imaged: whereas MSI projects might photograph in dozens of bands, HSI photographs in hundreds. The tradeoff is that although HSI obtains high spectral resolution, it offers comparatively poorer spatial resolution. This latter is the more valuable when seeking to recover lost text and images, making MSI generally the preferred tool for such a task. HSI, however, provides useful material data, thus offering scholars information about the production of an object. See, e.g., Di Bai, David W. Messinger, and David Howell, "Hyperspectral Analysis of Cultural Heritage Artifacts: Pigment Material Diversity in the Gough Map of Britain," *Optical Engineering* 56.8 (2017):081805,in which the authors uncover new data about the important medieval Gough Map and gain insight into patterns of creation and revision. HSI and MSI are thus both powerful tools, each suited to a particular suite of tasks.

2. Omissions and oversights are of course inevitable due the constraints of space and scope as well as to human error. The authors apologize for their limitations.
3. As MSI rigs are often custom-built to suit the specific needs and research goals of a given institution or scholar, there can be considerable variation between systems. In this overview, then, we have sought to describe the systems accurately in general, though of course any given system may differ in its particulars from the description given here.
4. For a more detailed description of an MSI system, see William Christens-Barry, Ken Boydston, Fenella France, Keith Knox, Roger L. Easton, Jr., and Michael Toth, "Camera System for Multispectral Imaging of Documents," *Proceedings of SPIE—The International Society for Optical Engineering* 7249 (2009):724908. Note, though, that some of the technologies described in this presentation have since been rendered obsolete; e.g., in a new generation of imaging systems, the Lazarus Project and R-CHIVE now employ 50-megapixel cameras instead of the 39-megapixel setup they describe.
5. See MegaVision, Inc., http://www.mega-vision.com.
6. See Phase One, https://www.phaseone.com.
7. Color sensors place a color filter mosaic or Bayer array between the lens and the image sensor, effectively designating every pixel as either red, green, or blue. By contrast, all pixels in a monochrome sensor gather all the light in every scene, effectively increasing resolution by at least one third. Bayer arrays have the advantage of producing three-band (RGB) color in a single capture. Monochrome sensors, when paired with LEDs in multiple wavelengths, must take the same shot multiple times, each

in a different wavelength. All the images in the visible wavelengths can then be combined into a multiband color image that by virtue of the extra bands, generates color images of a far higher fidelity.

8. A more detailed consideration of the technologies employed by EMEL can be found at "Technologies," Sinai Palimpsests Project, http://sinaipalimpsests.org/technologies.
9. Early incarnations of MSI systems (like the one used to study the Archimedes Palimpsest) and some systems still in use today use very bright broad-spectrum (white) light sources from which all wavelengths except the desired one are filtered—e.g., to capture green, all wavelengths except green are filtered out, and so on. This necessitates long exposure times, which, in conjunction with the bright light sources, have the unfortunate effect of warming the object under study. The advent of LEDs has solved this problem: LEDs emit almost no heat, and the manuscript is exposed only to that wavelength which is to be photographed. As a result, fully imaging an object using a modern system exposes the object to less total illumination than "the normal room light exposure required to prepare the object for capture." See Greg Bearman, Ken Boydston, and Bill Christens-Barry, "Measuring the Illumination Exposure of LED Illuminants in a Multispectral Imaging System," MegaVision, Inc., http://www.mega-vision.com/news/pdfs/LED_exposure_of_EV_System_at_IAA.pdf, 6.
10. The Lazarus Project is a member of Rochester Cultural Heritage Imaging, Visualization, and Education (R-CHIVE), a broader collaborative effort composed of scholars and students from various institutions and organizations.
11. Anyone who has worn a white shirt under a blacklight will be familiar with this phenomenon. There, the fabric of shirt is absorbing the invisible ultraviolet light and reemitting it downspectrum as visible blue light.
12. The Lazarus Project, for example, uses six filters in its filter wheel (UV block [Schott GG400], UV pass [Hoya U360], orange [O22], red [R25], green [G58], and blue [B47]), all of which selectively block some wavelengths while allowing others through.
13. Bill Endres of the University of Oklahoma has used RTI to examine the eighth-century Lichfield Gospels; the results can be seen and interacted with at Manuscripts of Lichfield Cathedral, https://lichfield.ou.edu/. See also Bill Endres, "More than Meets the Eye: Going 3D with an Early Medieval Manuscript," in *Proceedings of the Digital Humanities Congress 2012*, ed. Clare Mills, Michael Pidd, and Esther Ward (Sheffield, UK: Digital Humanities Institute, 2014), available at https://www.dhi.ac.uk/openbook/chapter/dhc2012-endres. This technology may be further combined with MSI to produce a technique known as spectral RTI, on which see Todd Hanneken, "New Technology for Imaging Unreadable Manuscripts and Other Artifacts: Integrated Spectral Reflectance Transformation Imaging (Spectral RTI)," in *Ancient Worlds in a Digital Culture,* ed. Claire Clivaz and David Hamidovic, Digital Biblical Studies 1 (Leiden, Netherlands: Brill 2016), 180–195. Hanneken has employed spectral RTI to recover text and data from the Jubilees Palimpsest; images and data, as well as further information on the technology and methodology, can be accessed through the project's Website, "The Jubilees Palimpsest Project: Pioneering the Recovery of Illegible Text from Ancient Manuscripts through New Tools in Digital Archaeology," Jubilees Palimpsest Project, http://jubilees.stmarytx.edu/.

14. Tom Melzbender, Dan Gelb, and Hans Wolters, "Polynomial Texture Maps," in *SIGGRAPH 2001: Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques* (New York: ACM, 2001), 519–529.
15. Todd Hanneken of St. Mary's University has developed a similar ImageJ tool to handle MSI RTI images; see Todd Hanneken, "Guide to Creating Spectral RTI Images," Jubilees Palimpsest Project, http://jubilees.stmarytx.edu/spectralrtiguide/; see also "Integrating Spectral and Reflectance Transformation Imaging Technologies for the Digitization of Manuscripts and Other Cultural Artifacts," Jubilees Palimpsest Project, http://jubilees.stmarytx.edu/integrating/, for an explanation of the technology. The toolkit can be found at "SpectralRTI_Toolkit," GitHub, https://github.com/thanneken/SpectralRTI_Toolkit; and at Todd Hanneken, "Integrating Macros," Jubilees Palimpsest Project, http://jubilees.stmarytx.edu/integrating/IntegratingMacros.ijm.
16. See Roger L. Easton and David Kelbe, "Statistical Processing of Spectral Imagery to Recover Writings from Erased or Damaged Manuscripts," *Manuscript Cultures* 7 (2014):35–46. For an in-depth examination of some of these and other methods, see Alejandro Giacometti, Alberto Campagnolo, Lindsay Macdonald, Simon Mahony, Stuart Robson, Tim Weyrich, Melissa Terras, and Adam Gibson, "The Value of Critical Destruction: Evaluating Multispectral Image Processing Methods for the Analysis of Primary Historical Texts," *Digital Scholarship in the Humanities* 32.1 (2017):101–122.
17. Keith Knox is designing Hoku, a free, cross-platform Java program that performs batch processing. See Keith Knox, "Hoku Software," Center for Imaging Science, Rochester Institute of Technology, http://www.cis.rit.edu/~ktkpci/Hoku_Software.pdf.
18. Julia Craig-McFeely and Alan Lock have compiled a useful guidebook,

aimed at the nonspecialist, on using Photoshop to improve manuscript legibility. See Julia Craig-McFeely and Alan Lock, *Digital Restoration Workbook* (Oxford: OSSC Publications, 2006), available at "Digital Restoration Workbook: An Introduction to Digital Restoration Techniques Using High Resolution Digital Images," Digital Image Archive of Medieval Music, https://www.diamm.ac.uk/publications/digital-restoration-workbook/. On the opportunities and difficulties of such digital editing, see Julia Craig-McFeely, "From Perfect to Preposterous: How Digital Restoration Can Both Help and Hinder Our Reading of Damaged Sources," in *Cantus Scriptus: Technologies of Medieval Songs: Proceedings of the 3rd Annual Lawrence J. Schoenberg Symposium on Manuscript Studies in the Digital Age, November 20–21, 2010*, ed. Lynn Ransom and Emma Dillon (Piscataway, NJ: Georgia Press, 2012), 125–141.

19. An exhaustive list of all teams and institutions in possession of an MSI system or systems has proved difficult to compile, but in addition to those discussed throughout, a partial list includes the British Library in London; the Library of Congress in Washington, DC; the Israel Antiquities Authority in Jerusalem; Passau University's Digital Cultures Lab in Bavaria, Germany; the Mesrop Mashtots Institute of Ancient Manuscripts in Yerevan; the Latter Day Saints Church History Library in Salt Lake City; the Wilhelm Institute of Image Permanence in Grinnell, IA; the Shanghai Museum; and the National Museum of China in Beijing, all of which possess systems built by MegaVision, Inc. In addition, University College London, the Dallas Museum of Art, the Smithsonian Institution, the John Rylands Library, R. B. Toth Associates, and Yale University all have systems of various makes. Some institutions have attempted to build in-house systems: Virginia Blanton of the University of Missouri Kansas City leads a project named CODICES and has developed one such prototype system with her team.

20. Analog MSI, however, is over a century old, beginning with Raphael Kögel in 1914 at the Palimpsest Research Institute at Beuron Abbey in Germany. The Archimedes Palimpsest is privately owned, but many objects that might benefit from imaging remain in use as active parts of living communities. For an exploration of some of the ethical and practical issues surrounding this latter situation, see Bill Endres, "Imaging Sacred Artifacts: Ethics and the Digitizing of Lichfield Cathedral St Chad Gospels," *Journal of Religion, Media and Digital Culture* 3:3 (2014):39–73.

21. For a full account of this long-term project, see Reviel Netz, William Noel, and Natalie Tchernetska, *The Archimedes Palimpsest: Volume Two* (New York: Cambridge University Press, 2011). See also William Noel and Reviel Netz, *The Archimedes Codex: How a Medieval Prayer Book Is Revealing the True Genius of Antiquity's Greatest Scientist* (Cambridge, MA: De Capo Press, 2007); and Roger L. Easton and William Noel, "Infinite Possibilities: Ten Years of Study of the Archimedes Palimpsest," *Proceedings of the American Philosophical Society* 154.1 (2010):50–76; as well as Roger L. Easton, William A. Christens-Barry, and Keith T. Knox, "Ten Years of Lessons from Imaging of the Archimedes Palimpsest," *Commentationes Humanarum Litterarum* 129 (2011):5–34. Images produced by the project have been made freely available at The Archimedes Palimpsest, http://www.archimedespalimpsest.org.

22. Then National Policy Director of the National Reconnaissance Office, now President and Chief Technology Officer of R. B. Toth Associates.

23. Respectively, Rochester Institute of Technology (RIT); Retired Dean of the College of Fine Arts at RIT, then at the Xerox Corporation, now Chief Scientific Advisor for EMEL. Then at Johns Hopkins University, now at Equipoise Imaging. For a fuller accounting of the teams and the organizational structure of the project, see Reviel Netz, William Noel, and Natalie Tchernetska, *The Archimedes Palimpsest: Volume One* (New York: Cambridge University Press, 2011), 2–5.

24. See Roger L. Easton, Keith T. Knox, William A. Christens-Barry, Kenneth Boydston, Michael B. Toth, Doug Emery, and William Noel, "Standardized System for Multispectral Imaging of Palimpsests," *Computer Vision and Image Analysis of Art* 753 (2010):75310D.

25. Netz, Noel, and Tchernetska, *Archimedes Palimpsest* 11.

26. These are 365 nm, 445 nm, 470 nm, 505 nm, 530 nm, 570 nm, 617 nm, 625 nm, 700 nm, 735 nm, 870 nm, 470 nm top (raking light illumination directed from the top of the manuscript), 470 nm bottom (raking light directed from the bottom of the manuscript), 870 nm top, 870 nm bottom, and under a broad-spectrum tungsten light.

27. The palimpsest contains Archimedes' On the Equilibrium of Planes, Measurement of a Circle, On the Sphere and Cylinder, On Floating Bodies, The Method of Mechanical Theorems, and the Ostomachion. Of these, Mechanical Theorems and the Ostomachion are otherwise lost, and no other copy of On Floating Bodies survives in Greek. For a transcription and discussion of the Hyperides text, see Natalie Tchernetska, "New Fragments of Hyperides from the Archimedes Palimpsest," Zeitschrift für Papyrologie und Epigraphik 154 (2005):1–6; and Andreas Janke and John Louis Nádas, The San Lorenzo Palimpsest, Florence, Archivio Del Capitolo di San Lorenzo, Ms. 221: Introductory Study and Multispectral Images, vol. 1 (Lucca, Italy: Libreria Musicale Italiana, 2016).

28. Janke and Nádas, *San Lorenzo Palimpsest*, 5–8.
29. Ibid., 5.
30. Ibid., 22.
31. Frank A. D'Accone, "Una nuova fonte del'Ars Nova italiana: Il codice di San Lorenzo, 2211," *Studi Musicali* 13 (1984):10–18.
32. Janke and Nádas, *San Lorenzo Palimpsest*, 1.
33. The digital archival record can be found at "I-FsI MS 2211 (San Lorenzo)," Digital Image Archive of Medieval Music, https://www.diamm.ac.uk/sources/194/#/.
34. For a fuller accounting of this endeavor, see Andreas Janke and Claire MacDonald, "Multispectral Imaging of the San Lorenzo Palimpsest (Florence, Archivio del Capitolo di San Lorenzo, Ms. 2211)," *Manuscript Cultures* 7 (2014):113–125, available at the Centre for the Study of Manuscript Cultures, Universität Hamburg, https://www.manuscript-cultures.uni-hamburg.de/MC/articles/mc7_Janke_MacDonald.pdf.
35. The use of cradles in this fashion is an industry commonplace, though they may be specially configured or built for individual projects; see above the discussion of the particularly advanced cradle employed the Sinai Palimpsest Project.
36. The CSMC team illuminated in 365 nm, 455 nm, 470 nm, 505 nm, 535 nm, 570 nm, 625 nm, 700 nm, 735 nm, 780 nm, 870 nm, 970 nm, and 1,050 nm. For fluorescence, five filters were used: UV pass, UV block, red, green, and blue. See Janke and Nádas, *San Lorenzo Palimpsest*, 9.
37. Currently, the text includes 126 texts in Italian, 80 in French, and 10 in Latin, though Janke and Nádas suggest that the manuscript may originally have contained three hundred or possibly even four hundred works. See ibid., 17. As with Archimedes, the results of this years-long effort were published in two volumes: the first providing introductory study and commentary on the book and the recovery process, and the other a facsimile edition collecting the multispectral images in yellow/blue pseudocolor. These images have not been made available online.
38. A strong case can be made as well for the application of MSI to the countless illegible manuscript fragments and bits of binder's waste that languish in collections across the world. For an example of one such scrap that proved significant, see Kyle Ann Huskin, Alexander J. Zawacki, and Gregory Heyworth, "Multispectral Recovery of a Fragment of Richard FitzRalph's *Summa de Questionibus Armenorum* from University of Rochester, D.460 1000-03," *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* (forthcoming).
39. The project has been supported by the Arcadia Fund. See Michael B. Phelps and Michael B. Toth, "Strategic Considerations for Palimpsest Imaging Projects: Lessons Learned from the St. Catherine's Monastery Palimpsest Survey," *Commentationes Humanarum Litterarum* 129 (2011):207–221. Of related concern is the Syriac Galen Palimpsest (formerly referred to as Zürich Or. 77), which was taken from St. Catherine's (where one leaf remains) at some point in the early twentieth century. The manuscript was acquired at auction in 2002 by an anonymous collector and lent in 2009 to the Walters Art Museum for study and imaging. The image data from this project have been made available under a Creative Commons license at "The Syriac Galen Palimpsest," OPenn Primary Digital Resources, University of Pennsylvania Libraries, http://digitalgalen.net/. The overtext is a liturgical text, known as *Oct□ēchos*, from the eleventh century; the undertext preserves portions of Galen's *Book of Simple Drugs* in Syriac translation, alongside other translations of Greek medical texts. For more on the texts contained within the Syriac Galen Palimpsest Project, see Naima Afif, Siam Bhayro, Grigory Kessel, Peter E. Pormann, William I. Sellers, and Natalia Smelova, "The Syriac Galen Palimpsest: A Tale of Two Texts," *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* 3.1 (2018):110–154. On the recovery project, see Michael B. Toth, "Pulling It All Together: Managing the Syriac Galen Palimpsest Project," *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* 3.1 (2018):9–32; Roger L. Easton, Keith T. Knox, William A. Christens-Barry, and Ken Boydston, "Spectral Imaging Methods Applied to the Syriac Galen Palimpsest," *Manuscript Studies: A Journal of the Schoenberg Institute for Manuscript Studies* 3.1 (2018):69–82; and S. Bhayro, R. Hawley, G. Kessel, and P. E. Pormann, "The Syriac Galen Palimpsest: Progress, Prospects and Problems," *Journal of Semitic Studies* 58.1 (2013):131–148.
40. Spectral images and transcripts are freely available at The David Livingstone Spectral Imaging Project, http://livingstone.library.ucla.edu/. See also A. Wisnicki and Michael B. Toth, "The David Livingstone Spectral Imaging Project," in *David Livingstone, Man, Myth and Legacy*, ed. Sarah Worden (Edinburgh: National Museums Scotland, 2012), 154–168. Phelps is helping to direct an initiative at Cambridge University to apply MSI to the Codex Zacynthius, a palimpsest now held at Cambridge University Library under the classmark MS Additional 10062, containing a thirteenth-century lectionary written over a seventh-century Greek witness to the Gospel of Luke (1:1–11:13) with commentary. This project is being carried out in conjunction with (among others) R-CHIVE members, including Easton, as well as Ira Rabin of Hamburg University, who works with both the CSMC (discussed above) and the Federal Institute of Material Research and Testing (Bundesanstalt für Materialforschung und -prüfung, or BAM).

Rabin's publications in the field of cultural heritage material studies are extensive, but see, e.g., Ira Rabin, Oliver Hahn, Roger Easton, Keith T. Knox, Ken Boydston, Gregory Heyworth, Timoty Leonardi, and Michael Phelps, "Initial Inspection of Reagent Damage to the Vercelli Book," *Comparative Oriental Manuscript Studies* 1.1 (2015):34–35. Her work, and that of her team, typically focuses not on textual recovery—by and large the focus of the present article—but on the material qualities of cultural heritage objects; see, e.g., Ira Rabin, Oliver Hahn, Timo Wolff, Admir Masic, and Gisela Weinberg, "On the Origin of the Ink of the Thanksgiving Scroll (1QHodayot)," *Dead Sea Discoveries* 16.1 (2009):97–106; and Ira Rabin, Oliver Hahn, and Mirjam Geissbühler, "Combining Codicology and X-Ray Spectrometry to Unveil the History of Production of Codex germanicus 6 (Staats- und Universitätsbibliothek Hamburg)," *Manuscript Cultures* 7 (2014):126–131. For a further multispectral examination of the Vercelli Book, see Gregory Heyworth, "New Light on the Vercelli Book: Textual Science and the History of the Book," in Old English Tradition: Essays in Honors of J. R. Hall, edited by Linda Brady. Medieval and Renaissance Texts adn Studies Series (Tempe, Arizona: ACMRS, forthcoming 2019).

41. "Palimpsests and Scholarship," Sinai Palimpsest Project, http://sinaipalimpsests.org/palimpsests-and-scholarship.
42. Richard Gray, "The Invisible Poems Hidden in One of the World's Oldest Libraries," *The Atlantic*, August 9, 2017, https://www.theatlantic.com/science/archive/2017/08/sinai-peninsula-hidden-texts/536313/; Sarah Gibbens, "Text by 'Father of Medicine' Found in Remote Egyptian Monastery," *National Geographic*, July 11, 2017, https://news.nationalgeographic.com/2017/07/hippocrates-manuscript-sinai-palimpsests-st-catherines-monastery-spd/.
43. Sinai Palimpsests Project, http://www.sinaipalimpsests.org/.
44. A detailed explanation of IIIF can be found at International Image Interoperability Framework, https://iiif.io/. For a list of plug and play software that works with IIIF images (including Mirador), see "Apps & Demos," International Image Interoperability Framework, https://iiif.io/apps-demos/.
45. Chet Van Duzer, "Multispectral Imaging for the Study of Historic Maps: The Example of Henricus Martellus's World Map at Yale," *Imago Mundi* 68.1 (2015):62–66, 62.
46. Chet Van Duzer, Henricus Martellus's World Map at Yale (c. 1491): Multispectral Imaging, Sources, and Influence (New York, NY: Springer Science Business Media, 2018), v–x.
47. This imaging was made possible through the support of a grant from the National Endowment for the Humanities. The map was previously

photographed under ultraviolet light in the 1950s by J. S. Sioid, enabling the recovery of some otherwise illegible inscriptions, but vast swaths of it remained too dim to make out. See J. S. Sioid, "Documents for the Technical Examination of the World Map Studied in Berne," June 1960 (a collection of natural-light, infrared, and ultraviolet images of the map), cited in Van Duzer, v, note 2.

48. This generation of lights were emitted at twelve frequencies from 365 nm to 940 nm.
49. Van Duzer, "Multispectral Imaging," 63.
50. The geographical features, toponyms, and shape of the southern and western coasts of Africa were illegible and almost invisible before MSI. Afterwards, Van Duzer was able to decipher several new inscriptions, including, e.g., "[]aterina," which matches the Behaim's Globe's Rio de Catherina. These toponyms are particularly important for deciphering Martellus's knowledge of Portuguese explorations in Africa. In Van Duzer, *Henricus Martellus's World Map*, 128.
51. For an example of this, see Gregory Heyworth and Daniel O'Sullivan, eds., *Les Eschéz d'Amours: A Critical Edition of the Poem and its Latin Glosses* (Leiden, Netherlands: Brill, 2013). A second volume of this edition, based on the more recalcitrant (because more badly damaged) second half of the manuscript (Dresden, Sächsische Landesbibliothek, Oc. 66) is in progress, edited by Heyworth and Kyle Ann Huskin. Findings may also be published, or at least announced, simply as blog posts; see, e.g., Becky Lawton, "New Records of Slavery from Anglo-Saxon Cornwall," *Medieval Manuscripts Blog*, British Library, February 15, 2019, https://blogs.bl.uk/digitisedmanuscripts/2019/02/new-records-of-slavery-from-anglo-saxon-cornwall.html.