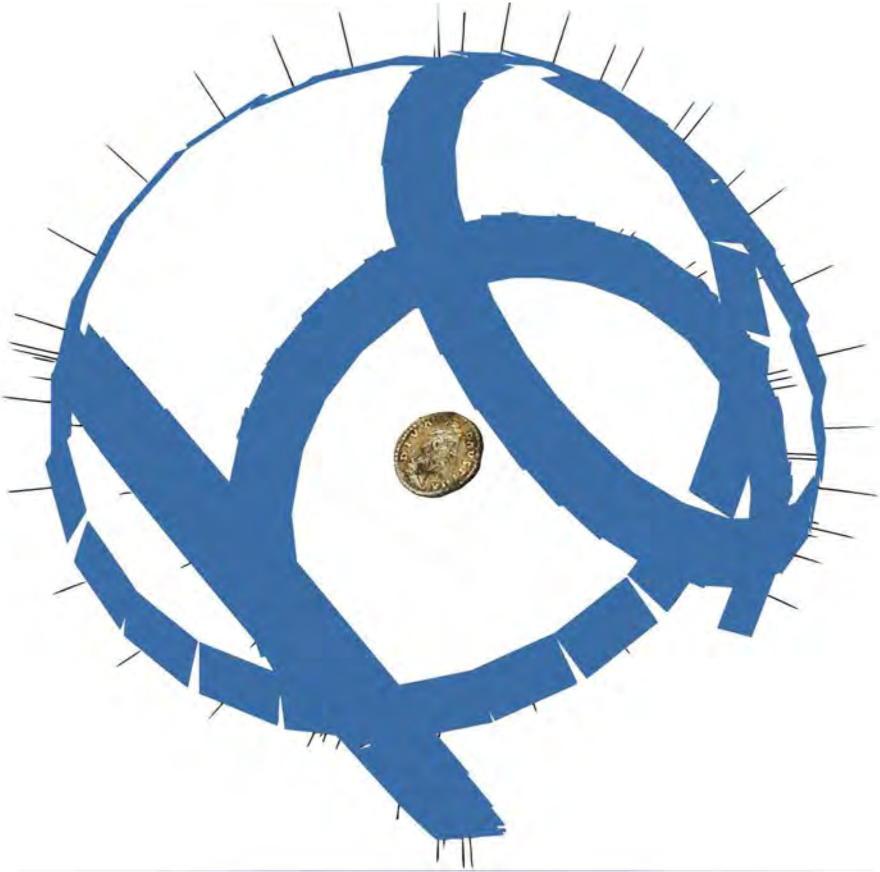

Collection Development, Cultural Heritage, and Digital Humanities

# DIGITAL TECHNIQUES FOR DOCUMENTING AND PRESERVING CULTURAL HERITAGE

Edited by ANNA BENTKOWSKA-KAFEL and LINDSAY MacDONALD

COSCH
COLOUR & SPACE IN CULTURAL HERITAGE

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# CONTENTS

## PART 2: METHODS AND TECHNOLOGIES

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# LIST OF ILLUSTRATIONS

## Figures

## Tables

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 3D | Three-dimensional |
| 4D | Four-dimensional |
| AAT | *Art & Architecture Thesaurus® Online*, Getty Vocabulary Program, J. Paul Getty Trust, USA |
| ACM | Association for Computing Machinery, USA |
| AHRC | Arts and Humanities Research Council, UK |
| AOTF | Acousto-Optical Tunable Filter |
| AR | Augmented Reality |
| ASME | American Society of Mechanical Engineers |
| ASTM | American Society for Testing Materials |
| ATR | Attenuated Total Reflectance |
| BHRT | Bosnia Herzegovina Radio Television |
| BIM | Building Information Modelling |
| CAD | Computer-Aided Design |
| CBIR | Content-based Image Retrieval |
| CCD | Charge-Coupled Device |
| CD-ROM | Compact Disc-Read Only Memory |
| CH | Cultural Heritage |
| CIDOC | International Committee for Documentation (within ICOM) |
| CIE | Commission Internationale de l'Éclairage |
| CIPA | Comité International de Photogrammétrie Architecturale (within ICOMOS) |
| CMM | Coordinate Measurement Machine |
| CMOS | Complementary Metal-Oxide-Semiconductor |
| CMS | Collection Management System |
| COSCH | Colour and Space in Cultural Heritage, COST Action TD1205, 2012–16 |
| COST | European Cooperation in Science and Technology |
| CPU | Central Processing Unit |
| CRISATEL | Conservation Restoration Innovation Systems for image capture and digital Archiving to enhance Training, Education and lifelong Learning (EU FP5-IST-1999-20163 project 2001–4) |
| CRM | Conceptual Reference Model |
| CT | Computed Tomography |
| DEM | Digital Elevation Map |

| | |
|---|---|
| DOI | Digital Object Identifier |
| DSLR | Digital Single Lens Reflex (camera) |
| ECCO | European Confederation of Conservator-Restorers' Organisations |
| ECI | Early Career Investigator |
| EDM | Electronic Distance Measurement/Meter |
| EDS | Energy Dispersive Spectroscopy |
| EDX | Energy Dispersive X-ray Spectroscopy |
| EPSRC | Engineering and Physical Sciences Research Council, UK |
| ERA | European Research Area |
| ESR | Early Stage Researcher |
| EU | European Union |
| FADGI | Federal Agencies Digitization Guidelines Initiative, USA |
| FTIR | Fourier Transformed Infrared Spectroscopy |
| FWHM | Full Width Half Maximum |
| GFC | Goodness-of-Fit Coefficient |
| GIS | Geographic Information System |
| GPS | Global Positioning System |
| GSD | Ground Sampling Distance |
| HBIM | Heritage Building Information Modelling |
| HD | High Definition |
| H-RTI | Highlight Reflectance Transformation Imaging |
| HSI | Hyperspectral Imaging |
| HTML | Hypertext Markup Language |
| ICCROM | International Centre for the Study of the Preservation and Restoration of Cultural Property |
| ICOM | International Council of Museums |
| ICOM-CC | International Council of Museums-Committee for Conservation |
| ICOMOS | International Council on Monuments and Sites |
| ICP | Iterative Closest Point (algorithm) |
| ICT | Information Communication Technology |
| IEEE | Institute of Electrical and Electronics Engineers, USA |
| IET | The Institution of Engineering and Technology, UK |
| IFAC-CNR | Istituto di Fisica Applicata Nello Carrara, The Nello Carrara Institute of Applied Physics in Sesto Fiorentino, Italy, part of the National Research Council (CNR) |

| | |
|---|---|
| IS | Imaging Spectroscopy |
| ISO | International Organization for Standardization |
| ISPRS | International Society for Photogrammetry and Remote Sensing |
| IVE | Interactive Virtual Environment |
| JCGM | Joint Committee for Guides in Metrology |
| Laser | Light Amplification by Stimulated Emission of Radiation |
| LCTF | Liquid Crystal Tunable Filter |
| LED | Light-Emitting Diode |
| LIBS | Laser-Induced Breakdown Spectroscopy |
| LIDAR | Light Detection and Ranging (remote sensing) |
| LS | Laser Scanning |
| MARC | Methodology for Art Reproduction in Colour (EU FP3-ESPRIT 6937 project 1992–95) |
| MoU | Memorandum of Understanding |
| MSI | Multispectral Imaging |
| MVS | Multiple View Stereovision |
| n/a | not applicable |
| NEH | National Endowment for the Humanities, USA |
| NIR | Near Infrared |
| OBJ | Computer file format for 3D geometry definition |
| OIML | International Organization of Legal Metrology |
| OWL | Web Ontology Language |
| PEG | Polyethylene Glycol |
| PGP | Prism-Grating-Prism |
| PLY | Polygon File (computer file 3D format) |
| PS | Photometric Stereo |
| PTFE | Polytetrafluoroethylene |
| PTM | Polynomial Texture Mapping |
| PXRF | Portable X-ray Fluorescence (Spectroscopy) |
| R&D | Research and Development |
| RDFa | Resource Description Framework in Attributes |
| RGB | Red Green Blue |
| RIC | *The Roman Imperial Coinage* (see Mattingly and Sydenham 1923) |
| RMSE | Root-Mean-Square Error |
| ROV | Remotely Operated Vehicle |

| | |
|---|---|
| RRT | Round Robin Test |
| RS | Recommender System |
| RTI | Reflectance Transformation Imaging |
| SEM | Scanning Electron Microscopy |
| SfM | Structure from Motion |
| SIVT | Spatial Image analysis and Viewing Tool |
| SLI | Structured Light Imaging |
| SLR | Single Lens Reflex (camera) |
| SLS | Structured Light Scanning |
| SOP | Standard Operating Procedure |
| SPD | Spectral Power Distribution |
| SPIE | Society of Photographic Instrumentation Engineers |
| STSM | Short-Term Scientific Mission |
| SWIR | Short-Wave Infrared |
| TIN | Triangulated Irregular Network |
| TLS | Terrestrial Laser Scanner |
| TOF | Time of Flight |
| UAV | Unmanned Aerial Vehicle |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| URL | Uniform Resource Locator |
| USB | Universal Serial Bus |
| UV | Ultraviolet |
| VASARI | Visual Art System for Archiving and Retrieval of Images (EU FP2-ESPRIT 2 project 1989–92) |
| VDI/VDE | Verein Deutscher Ingenieure / Verband der Elektrotechnik Elektronik Informationstechnik |
| Vis | Visible |
| VNIR | Visible and Near Infrared |
| VR | Virtual Reality |
| VRML | Virtual Reality Modelling Language |
| WG | Working Group |
| XML | eXtensible Markup Language |
| XRF | X-ray Fluorescence Spectroscopy |

# FOREWORD

COSCH stands for Colour and Space in Cultural Heritage and represents four years of networking activities of scientists and researchers from other disciplines from twenty-eight European countries. They share a dedication to improving the understanding of optical measurement techniques, applied to various tasks in documentation of material cultural heritage. The COSCH network benefited from the support and funding of the European Cooperation in Science and Technology, commonly known as COST. COST was founded in 1971 as an intergovernmental framework for cooperation in science and technology and is one of the oldest European bodies funding networking in these areas. Cooperation is implemented through the so-called Actions, such as COSCH. A COST Action provides a platform for dialogue and exchange of interdisciplinary knowledge amongst researchers from different academic disciplines, as well as industry and commercial research laboratories.

COST Actions have a funding period of four years. The funding covers networking activities, mainly the cost of organizing and travelling to meetings, conferences, and workshops. Financial support is also available for research exchange visits (so-called Short-term Scientific Missions, or STSMs), training schools, publications, and other dissemination activities. Personnel costs cannot be funded, which distinguishes COST Actions from research projects supported through the framework programmes of the European Union, such as Horizon 2020 and the earlier 7th Framework Programme (FP7) for Research and Technological Development. The networking character of COST Actions is paramount. Despite the lack of research funding, COST Actions have nonetheless a clear scientific focus that guides work conducted in the course of all activities. COST takes a bottom-up approach to the selection of proposals for funding: any kind of scientific objectives held by an international group of researchers may compete for support, if it fits within the COST implementation rules. When accepted, a proposal is transformed into a Memorandum of Understanding (MoU) and is signed by all participating countries. This document defines the objectives, programme of work, its milestones and measures to be implemented by the Action. The summary of the COSCH MoU (2012, p. 3) reads:

> True, precise and complete documentation of artefacts is essential for conservation and preservation of our cultural heritage (CH). By ensuring access to the best possible documentation of artefacts we are contributing to the enhanced understanding of material CH and help its long-term preservation. We are all responsible for ensuring that this heritage is

> passed on to future generations. Documentation of CH involves researchers, scientists and professionals from multiple disciplines and industries. There is a need to promote research, development and application of non-contact optical measurement techniques (spectral and spatial) adapted to the needs of heritage documentation on a concerted European level, in order to protect, preserve, analyse, understand, model, virtually reproduce, document and publish important CH in Europe and beyond. Research in this field typically relies on nationally-funded projects with little interaction between stakeholders. This Action will provide a stimulating framework for articulating and clarifying problems, sharing solutions and skills, standardising methodologies and protocols, encouraging a common understanding, widening applications and dissemination. The Action will foster open standards for state-of-the-art documentation of CH. It will simplify the usage of high-resolution optical techniques in CH and define good practice and stimulate research.

COSCH represents four years of intense interdisciplinary work, to the benefit of our common cultural heritage, aimed at optimizing its documentation through a better understanding of technology, and its dependencies on the questions and requirements of specific applications. Exemplary case studies in applied technology, in accordance with identified guiding research questions, are the main subject of this book. They represent the practical work which has been conducted in order to meet the COSCH objectives.

Frank Boochs
COSCH Chairman

# INTRODUCTION

ANNA BENTKOWSKA-KAFEL

This book presents some of the outcomes of interdisciplinary research and debates conducted by the participants in the international network, Colour and Space in Cultural Heritage (COSCH) between 2012 and 2016. The book adds to a large body of literature on the applications of digital technologies to the study and preservation of cultural heritage. So why was another book on the subject needed? In this introduction the rationale for the book, its scope, and methodology are explained.

## Cultural Heritage

After a certain period of time, human cultural activities and their products acquire the status of cultural heritage. The International Council on Monuments and Sites (ICOMOS 2002, 21) defines cultural heritage broadly as "an expression of the ways of living developed by a community and passed on from generation to generation." Some standard definitions of cultural heritage, both tangible and intangible, in the context of 3D documentation, have been collated by the consortium, 3D-COFORM (Arnold et al. 2009, 16–19).[1]

No single book can cover the variety and richness of cultural heritage, or the methods of its documentation. The limitations are inevitable. The COSCH network limited its interests to material objects of the cultural heritage of Europe, some of which are covered in this book. The objects and sites come from different periods and bear witness to different cultures. They vary in scale and materials, significance and value. They include an ancient Greek vase, the Karabournaki kantharos (chapter 2); Roman silver coins, the denarii of Faustina the Elder (chapter 3); painted wall decoration of the medieval French château of Germolles (chapter 4); a fortress overlooking Sarajevo, steeped in the multicultural, turbulent history of Bosnia (chapter 5); a medieval wooden shipwreck, known as a cog, lifted from a river bed in Germany (chapter 7); and a variety of historic objects housed by the National Museum of Romanian History, Bucharest, including icons, illuminated manuscripts, and pottery (chapter 6). Other works of world art and architecture, as significant

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1 Major research projects in this area are often better known through their acronyms than full names, some of which tend to be very long and when used in a sentence distract from the main argument. The acronyms used by the authors can be found, spelled out, in Selected Bibliography, p. 277, see also Acronyms and Abbreviations, p. xxvii.

as the ancient, rock-cut statues of Buddha in the Bamiyan Valley in Afghanistan, demolished by the Taliban in 2001, are mentioned in the second part of the book. This small selection is representative of other art, crafts, and architecture, in various states of preservation and restoration that can be found *in situ* or housed in museums.

COSCH was established to enhance and promote specialist applications of optical technologies to the spatial and spectral recording of material cultural heritage. The research processes and some digital outputs of such applications (both digitally born and digitized) represent cultural heritage in its own right and require effective digital preservation. The significance of digital heritage has been recognized by UNESCO (2003b). Museum collections, archives, and other heritage organizations, motivated to some extent by a growing public demand, are under pressure to digitize their holdings. Yet we need to remember that only a small proportion of world cultural heritage has been digitized. The automation of digitization is seen as a way forward (Karaszewski et al. 2014), but not without concerns over the quality achieved by fast and uniform machine processes applied to unique objects. Issues of long-term digital preservation are also common. As noted in chapter 7, the long-term maintenance and access to digital tools and resources remain problematic, constituting a major barrier to the wider adoption of digital research methodologies. Only a fraction of digital assets thus created since the 1980s continue to be wanted, accessible, and usable. Technical solutions to digital obsolescence are available, but there are other reasons for neglect of electronic resources created in the past. The 3D computer model of the Old Minster in Winchester, created by archaeologists of the site in collaboration with IBM Research UK in the mid-1980s (3DVisA, 2006) exemplifies how research methods and outcomes that were cutting-edge in their day have fallen behind current expectations of digital, interdisciplinary scholarship. The model nonetheless represents an important step in the history of digital scholarly collaborations and is worthy of inclusion in a museum of computing or a museum of virtual archaeology.

## Colour

Those new to the name, Colour and Space in Cultural Heritage, will read into this phrase a preconceived understanding of colour and space. Both concepts are so familiar to the experience of cultural heritage and life in general, that an explanation may seem redundant. An understanding of the concepts will, however, differ from one reader to another, so much so that a common understanding must not be assumed.

Colour "is the child of light, the source of all life on earth" (Delamare and Guineau 2000, 13). Johann Wolfgang von Goethe (1810) believed that colour is a level of darkness. He disputed Isaac Newton's (1704) discovery of the spectrum—the rainbow of colours of visible light after it passed through a prism. Newton's drawing of what he termed the "crucial experiment" (Newton 2010) shows sunlight refracted into five constituent colours, as he could not quite decide upon their number. The diagram, in black ink on paper, is a lasting, graphic record of his discovery process. Although since dismissed by modern science, Goethe's intuitive and poetic ideas about science and psychology of colour have continued to influence cultural theories. Since the earliest known cave paintings, artists have had a very special relationship with colour, not only physical, even tactile, but primarily spiritual. Our visual response to colour is emotional.

Colour in the arts is associated with pigments used to make paint, and dyes to colour textiles, but also with musical analogies to tint, tone, and hue, and further to chromatic harmony. From the quantifiable measures of the physical properties of colour to the significance of colour as an indicator of race, the range of possible references to cultural heritage is endless. The power of colour is forcefully expressed in the painting *Potent Fields* (2002, British Museum, London) by the South-African artist, Karel Nel, in which two planes, one in white ochre and the other in dark red ochre, refer to the separateness (apartheid) of colour. This powerful reading is only apparent to the informed beholder. Artwork detached from its message and context risks being meaningless. One must recognize that no documentation of a material object is ever complete unless its historical, social and phenomenological, spiritual and symbolic aspects are also studied. Conservation and heritage science are also capable of bringing back some of the lost meaning. Discolouration of paint or varnish over time, for example, influences the perceived meaning of art, as the well-known painting by Rembrandt van Rijn, showing a militia group portrait in daylight, continues to be popularly called *Night Watch* (1642, Rijksmuseum, Amsterdam).

Colour and Space in Cultural Heritage was led by the Technical University of Applied Science in Mainz, the COSCH Action grant holder. COSCH participants met in many different places in Europe, also in Mainz, which is famous for being the birthplace of Johannes Gutenberg and an apt place to deliberate the progress in documentation and reproduction technologies. For those who love the exuberance of colour in art, St. Stephen's church in Mainz is a perfect destination. The stained-glass windows there were designed by the ninety-year-old Marc Chagall, who was, according to Picasso, the only painter (after Matisse) to understand colour. "When Matisse dies," Picasso is known to have said, "Chagall will be the only painter left who understands what colour really is."[2] The colour scheme is

**2** Françoise Gilot and Carlton Lake, *Life with Picasso* (London: Virago, 1990), 265.

predominantly cobalt blue with vivid accents of red, black, and yellow, ever changing in the daylight. The glowing effect is spiritual, even heavenly for some. What influences the artist's choice of paint or draws the viewer to particular colours may be investigated from aesthetic, psychological and many other perspectives. While recognizing this, the COSCH network's research into this area, however, has primarily been scientific with a focus on the capture of the intensity of radiation reflected at each wavelength from each point on a coloured surface (see, for example, Casini et al. 2015; Nascimento et al. 2017).

When in the early 2000s the Corpus Vitrearum Medii Aevi embarked upon digitization of medieval stained-glass that have survived in Great Britain (www.cvma.ac.uk), it surprised everyone how well the luminous effect of digital images displayed on a monitor screen, then glass, simulated the viewing of actual stained-glass windows. This was a visible, positive point of digitization. The process had many critics. Digitization in those days mainly involved scanning slides (particularly in teaching collections), negatives, and photographic prints. The laboriousness and exorbitantly high costs were of concern. A blank CD-ROM, then a popular portable data storage medium, retailed at approximately £12/$18 each in 1998, and could hold no more than 650MB of read-only data. Various major technical issues involved in the processing and storing of digital data, their presentation and dissemination have since been resolved. Importantly, the direct digitization of the artefact, without the intermediary of a photographic surrogate, is now not only possible, but commonplace. Although amateur photographers rarely control the quality of the photographs they take, tending to rely on factory colour settings of the device, professionals carefully set up the lighting and calibrate the hardware, and not only manage, but also measure colour at all stages of the photographic and imaging processes, from capture through to application.

The importance of colour accuracy in art and heritage studies cannot be overestimated. It is perhaps surprising that black-and-white prints still prevail in many art books, even those on painting and colour studies. The popular book, *Art of Seeing* by John Berger, frequently reprinted by Penguin, may serve as an example. The superior quality of print reproduction of art, that has become available since the 1990s, is a result of years of research into colorimetric imaging. Notable international research projects in this area included VASARI (mentioned in chapter 8), MARC and MARC II, and CRISASTEL, carried out by major European information technology companies in association with museums and conservation institutes from 1989 through the 2000s. Prototype scanners enabling direct digitization of a painting, without the intermediary of photographic material, were developed and implemented at the Doerner Institute in Munich, the National Gallery in London, and the Uffizi Gallery in Florence. Another lasting effect of these historic imaging developments is the service known as Print-on-Demand, offered by some museums to visitors and online: customers can order a superior quality print, on canvas-textured paper, of a painting of their choice. CRISASTEL also pioneered the transmission of large image files over a network, today taken for granted. Black-and-white photography is art in itself, but one can only be pleased that greyscale prints, so common in the past, no longer predominate in newly created visual records.

There is more to colour than meets the eye. The colour that is invisible to the human eye is a subject of aesthetic theories of art that explores the effect of mental "after-images" that we can see, with the eyes closed, having previously stared at the sun or another light source. Władysław Strzemiński's abstract *An After-image of Light. A Lady at the Window* (ca. 1948, Museum of Art, Łódź) evidences such an artistic exploration. COSCH's scope of scientific research into colour extended to spectral imaging techniques and devices in the visible (380–750nm), near infrared (750–1000nm), and infrared (1000–2500nm) ranges. "The combination of digital imaging with spectroscopy has expanded point-based, or one-dimensional (1D) spectroscopic techniques. Imaging spectroscopy provides the ability to distinguish and map the spatial distribution of materials over an entire object, extract reflectance spectra for the identification of materials, calculate colour, enhance and reveal underdrawings, detect changes in composition, and identify damage and past conservation treatments" (p. 142). A group of scientists and other researchers within the COSCH network carried out a Round Robin Test (RRT), discussed in chapter 8, to assess the current diversity of systems and methodologies, aiming at more standardization and quality control.

## Space

"Colour is all," believed Chagall. "When colour is right, form is right."[3] This artistic observation points towards one of the most pertinent relationships in the arts and in our experience of the external world, that between colour and form. The COSCH network's understanding of space was predominantly scientific. In the context of COSCH research interests, space is synonymous with the three-dimensionality of material objects: the geometry of the object, including architecture and other physical structures. Therefore, space in this book is primarily considered as measurable, geometrical properties of material objects, and a subject of 3D optical metrology. Geographical terrain, or phenomenological experiences of space, or

**3** Citation after Chagall "Colour Is Everything," Spring exh., William Weston Gallery, London, 16 April 2015, http://www.williamweston.co.uk/exhibitions/items/133 (accessed 15 October 2016).

anthropological approaches to a place, all of which are relevant to cultural heritage, were outside the scientific objectives of COSCH research, although they had to be addressed, if only marginally, in the context of 3D historical visualization (COSCH Working Group 5). Time, inherent to the experience of space, is considered in the same context, and referred to, for convenience, as the 4D presentation of cultural heritage (chapter 5). A dedicated COSCH working group was preoccupied with spatial object documentation: the methods and instruments for the acquisition and processing of 3D data. Photogrammetry, 3D laser scanning and total station surveying, structured light scanning and Structure from Motion are amongst 3D sensing techniques employed in COSCH studies, covered in the chapters that follow. Historical visualization of cultural heritage was generally seen as a by-product of 3D data acquisition and processing. Arts and humanities scholars and the general public are likely to evaluate visualization, based on its appearance and realism of rendering, rather than its geometry. The characteristics of these and other methods are explained and discussed; ample exemplars of applications to cultural heritage are provided, with further references to significant non-COSCH projects and literature. One should bear in mind that Euclidean space and linear time, both deeply rooted in Western cultures, are amongst other possible concepts of past cultures.

## Science and Technology

The relationships between science, technology, and cultural heritage, described as “inexorable” (Rogerio-Candelera 2014, xi) have been widely researched (MacDonald 2006; Barber and Mills 2011; Stanco et al. 2011). The COSCH network was established as a trans-domain COST Action (TD 1201) in Materials, Physical, and Nanosciences. Participating scientists and engineers included experts in material sciences, conservation, chemistry and physics, photonics, imaging and a range of other fields in computer science. The participation of humanities scholars and other non-scientists in a network dedicated to materials, physical, and nanosciences is an unusual feature.

The material and technology used in the making of an artefact determines its formal characteristics, as well as aesthetic qualities and its value. One of the COSCH working groups focused on the conservation science of the surfaces of material objects. The case study described in chapter 4 concerns the examination of art materials that led to their identification, supporting the dating and attribution of the work, namely medieval wall paintings rediscovered under modern plasters. Art materials and techniques may also, albeit not necessarily, determine the cultural and artistic significance of the work (both are subject to fashion and other fluctuating, subjective factors), providing insights into the technical history of cultural heritage. Outdoor Impressionist painting, characterized by impasto, would not have been possible without the invention of quick drying oil paint. Le Corbusier's architecture would be very different without reinforced concrete. Technology affects the preservation, conservation, study, and communication of material culture.

Long before the digital era technology was being applied in the conservation of art and architecture to great, albeit occasionally disastrous effect (chapter 4). For example, microscopic analysis of pigments and dendrology helped the authentication and dating of paintings on wooden panels; and the application of photogrammetry to architecture was applied, among others, in the rebuilding of the Castle Howard in Yorkshire, England, after it was partly damaged by fire in 1940 (Thompson 1962). Accurate dimensions for restoration were calculated from available old photographic prints that had been taken with no photogrammetry in mind.

An important area of COSCH research has implications for *all* computer-based activities, namely algorithms. Invisible to most users, algorithms determine the effectiveness of applications of digital technology. Much work, led by a dedicated working group, was carried out to offer guidance in this difficult area. The problem of calibration, for example, is much greater than mentioned above. "The main problem with calibration accuracy is that it is both device dependent and application dependent. Thus, the calibration process used for a laser scanning system may differ from the calibration processes used for point-based spatial recording, spatial fringe projection, spatial photogrammetry or tactile measurement" (Trémeau and Murphy 2016, 2).

Good understanding of algorithms that support optical recording and examination of material objects was fundamental to the correct representation of the relevant know-how. So in the COSCH Knowledge Representation ($COSCH^{KR}$), described in chapter 9, "The COSCH Algorithm Selection Module (COSCHASM) has been defined formally to represent several processing chains used in Cultural Heritage as a hierarchy of algorithms to denote the types (from acquisition to visualization), properties (e.g., accuracy) and inter-relationships (e.g., between parametric factors) of algorithms used for a given task (e.g., 3D reconstruction of a Greek vase in the Kantharos case study exemplar). The main specificity of the COSCHASM is that it is aimed at end-users (who are non-experts in computer vision) in order to help them to find/select the best sequence of algorithms corresponding to their application" (Trémeau and Murphy 2016, 8).

As with other areas of study, digital technology has exponentially enhanced and expanded applications, while raising new issues. Digital data captured for one particular purpose may be reused for another. However, the advantages of applying digital technology to the examination and documentation of material culture cannot be taken for granted. The benefits need to be evidenced. Technical innovation must acknowledge earlier relevant research and be sympathetic to those traditional research methods that continue to be effective. A combination of different research methods enhances the critical evaluation of the chosen approach, often bringing a better understanding of the data under investigation and, ultimately, new insights into the subject of study. Chapter 4 demonstrates the significance of archival research conducted concurrently with a technical investigation of historic wall paintings. The virtual reconstruction of a fragmented ancient vase, covered in chapter 2, would be futile unless based on archaeological knowledge and earlier comparative studies of Greek pottery, including those communicated through text and hand drawings.

The limitations of digital technologies and related know-how need to be communicated to stimulate further research and this is one of the aims of this book. Another aim is a transparent account of areas prone to errors, including the failures of our research, to prevent others from repeating the same mistakes and take research forward. The aim of integrating spatial and spectral instruments and software, currently used independently, and to enhance the fusion of heterogeneous data, remains an ambitious and difficult goal. Many issues within individual technologies remain. Two studies in particular, those of silver coins and the Round Robin Test, described in chapters 3 and 8 respectively, applied a range of recording and analytical technologies to the same objects in order to compare and evaluate how results depend on a particular setup or operator. A number of problems were encountered due to: differences between instruments, software, and algorithms; the heterogeneity of captured data and file formats that can be generated and the profusion of standards and different claims to best practice. As pointed out in chapter 1,

> One should not underestimate the importance of describing and documenting well the used measurement methods and procedures, as these contribute to the determination and understanding of the overall quality of the measurement results and, at the same time, to a better analysis and interpretation of the measurand—the cultural heritage object in context—in this case. . . . "repeatability" measures the variation in measurements taken by a single instrument or operator under the same conditions (including same location, instrument, operator, procedure) and repetition over a short period of time, "reproducibility" measures the variation in measurements under a reproducibility set of conditions (e.g., different location, instrument, operator, procedure). Put simply, it measures the ability to replicate the results of others. (p. 6)

The COSCH network was primarily preoccupied with applied optical technologies. This book makes clear the connection between technology and its application(s). In the second, strictly technical part of the book, selected technologies employed in COSCH case studies are explained in the wider context of international research, with additional examples and suggestions for further reading. The explanations are aimed at both specialist and non-specialist readers. Each entry consists of a definition which introduces the basic principle of the technology or method, followed by a more detailed, specialist description and selected examples of significant projects.

## Methodology

Conference papers exploring the relationships between cultural heritage and technology constitute a considerable part of the literature in this area. Published relatively quickly, conference proceedings are indispensable sources for the latest innovation. Significant collections of diverse practice-based academic papers have been published in book format (Rogerio-Candelera 2014; Ioannides and Quak 2014; Stylianidis and Remondino 2016). Such collections, broadly responding to a generic theme in cultural heritage and technology, are not necessarily consistent in approach and research methodology. The collection of papers in this book is deliberately different. The chapters present the outcomes of carefully designed COSCH case studies dealing strictly with applications of optical technologies, spatial and spectral, to the study of material cultural heritage. In 2012 COSCH issued a call for proposals for case studies that would adhere to the scientific and interdisciplinary objectives of the Action. The call was issued with relevant methodological advice and references to standard literature on case study research.

Discussions held during the course of the COSCH Action showed that it is quite common to confuse a case study with use case or an exemplar application. A case study and use case are not synonymous with an exemplar (typically of a particular practice or project). Case studies and use cases are both forms of detailed empirical research into a particular situation and behaviour. Both require data collection and data analysis. To demonstrate the reliability of a case study, or use case, it is necessary to demonstrate that the operations can be repeated with the same results. Should one expect the same accuracy from instrumentation of comparable specification, irrespectively of how and where the recording took place? Is the human operator an affecting factor? COSCH case studies have demonstrated that this is far from being straightforward. The COSCH Round Robin Test (chapter 8) served as an experiment conducted in multiple laboratories to understand better the factors that affect the results of imaging spectroscopy techniques, applied to the same artefacts, in particular the differences in the instrumentation and data acquisition methods, and their effects on the accuracy and reliability of the acquired data. The COSCH case study of historic silver coins (chapter 3) involved experimenting with various spatial recording and analytical technologies, applied to the same test coins, in order to compare the quality of the acquired data.

In applied technical research a use case is a method in software and systems engineering. It seeks to establish how a human or machine system is able to achieve an objective specified *a priori*. Case study research combines quantitative and qualitative methods with the emphasis on human participants, and is more common in social sciences. It also seeks to determine how one condition leads to another (internal validity), but only for explanatory or causal studies. The other types of case study research, descriptive or exploratory, may be designed differently, but should equally demonstrate "external validity, i.e. define the domain to which a study's findings can be generalized" (Yin 2014, 46). Bearing in mind the interdisciplinary complexity of research into cultural heritage, the choice of case study methodology offered the required flexibility, without jeopardizing the integrity of individual disciplines and without curtailing innovation. Importantly, six types of sources that may be used in case study research include the evidence of the physical object, which is critical to the COSCH research covered in this volume. The reader will be able to judge the quality of response to the COSCH call for case studies, and the level of success in adopting this approach while seeking coherence in intellectual complexity and technological diversity. When dealing with this challenge human limitations and financial restrictions played a part. They were manifest in planning, organization, and delivery of tasks in the course of what was generally voluntary work.

## Knowledge through Documentation

Documentation is the key concern that connects all the contributions to this book. Documentation is "The already existing stock of information. As an activity, it stands for the systematic collection and archiving of records in order to preserve them for future reference. It can be said: Today's recording is tomorrow's documentation." According to the same source, recording "is in a broad sense, . . . the acquisition of new information deriving from all activities on a heritage asset, including heritage recording, research and investigation, conservation, use and management, and maintenance and monitoring" (Letellier et al. 2007, iv).

Although not a subject of systematic and comprehensive study by COSCH, the formats, standards, and management of documentation were relevant to many COSCH projects. The Roman coin case study (chapter 3) sought to establish connection between historic and current museum documentation practice and heritage science, looking specifically at the relationships between a standard museum object record, technical metadata (such as 3D measurements, results of chemical and elemental analyses), and iconographic records other than 2D photographs. Documentation, both the process of and its outcomes, was variably understood by COSCH researchers as: digitization/recording/surveying/measuring of a historic material object of cultural significance. All these terms were used interchangeably, prompting a need for in-depth, critical discussion of terminologies used by the COSCH interdisciplinary community, and generally in cultural heritage research (see chapter 1). The clarity of discrete disciplinary differences was essential for effective communication (see chapter 10).

Technical documentation that employs scientific methods of recording and analysis may be produced independently of historical and other cultural knowledge about the object. A basic responsibility of the museum, and other custodians of cultural heritage, is to keep records of every object in their care, even if the object is obscure to scholars and likely to remain in store awaiting study. This critical legal and conservation objective continues to be met predominantly through photography, manual measurements, and notes. The benefit of applying advanced optical recording technologies to cultural heritage is best manifested when—apart from recording the object's appearance and condition—the process also serves critical investigation with the potential of bringing about new insights into the interpretation of the object: its authenticity, provenance, historical use, and transformation. Comprehensive object documentation consists of technical records based on scientific information, alongside all other available records (visual, textual, audio, and in other formats) of the object, pertaining to its material and immaterial aspects, past and present. "It is the cultural heritage question one wishes to answer that determines the key properties that need to be documented [or recorded] and described in any given situation for a given cultural heritage object," state the authors of chapter 1 (p. 5). COSCH researchers were broadly in agreement that the best method of documentation may only be chosen based on the specific, object-related questions. Choosing the provider of the appropriate technology requires some level of familiarity with the technical options possible, and sustainability of outcomes, a familiarity which the object custodians may not have.

As part of its aim to foster applications of optical technologies for the documentation of material cultural heritage, the COSCH network sought to structure relevant information about applications, methods, and instruments. Based on information science and semantic technologies, a formal representation of this specialist interdisciplinary knowledge was discussed, designed, and implemented through a dedicated online platform, $COSCH^{KR}$ (see chapter 9 and http://cosch.info/coschkr-treeview). The responsiveness of the ontology to ever progressing knowledge—scientific, technical, and cultural—proved to be a true intellectual challenge. The design and development of the $COSCH^{KR}$ was one of the areas of

COSCH research that required a good understanding of conservation and scholarly documentation practices; good enough to be able to determine how advanced spatial and spectral technologies may effectively support cultural heritage professionals and scholars in their practice.

Art and science are forms of knowledge. A few glimpses into the aesthetic thought and practice of a single artist, Chagall for example, suffice to confirm the complicated, multidimensional nature of colour and space. Some dimensions cannot be measured. Owing to this complexity, optical technologies can only offer a part-solution to comprehensive object documentation. However, the significance of this contribution cannot be stressed enough. Recording yields data which, through processing and interpretation, bring about information that is required to acquire new knowledge. The realization of the significance of interpretative processes for the advancement of knowledge results in the necessity to record not only the process of recording, as advocated above, but the entire research process. Therefore paradata, recorded alongside metadata, are critical to scholarship, even more so to those digital scholarly processes which progress from one step to another without leaving behind visible traces of how one has arrived at the result. Paradata and other forms of *scholia* are necessary to ensure the transparency of the process, to enable its repetition and revision (Bentkowska-Kafel et al. 2012).

The WinSOM software, designed for the solid modelling of Winchester Old Minster, cost several times more than the funding of the COSCH network which, some thirty years later, has facilitated the studies of some 240 international researchers over four years. Applications of cutting-edge technology may be worth the great effort and investment even if they are eventually superseded by better solutions. The contributors to this book make persuasive arguments about the long-term, cognitive benefit of the digital documentation of cultural heritage, the value of which is independent of the technology that enabled new insights into the subject of study. We hope that our readers, specialists and non-specialists alike, find the chapters herein, which are representative of our work, valuable for developing and recording their own digitization projects and that they spark new research questions for the cultural heritage community.

The companion website with additional material, some interactive and in 3D, can be found at https://coschbook.wordpress.com.