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Digital imaging

1.1 Introduction

Digital imaging is enhancing the study of art much as it is enhancing nearly every scholarly endeavor, from medicine, chemistry, and astronomy, to ecology, biology, and geoscience. Seeing an artwork directly is highly desirable for any technical art analysis, of course, but it is not always possible nor is it often sufficient. Even for well–known works, such as Leonardo's *Mona Lisa*, close, careful study of the work out of its frame and without its protective bulletproof glass is generally reserved for select scholars and conservators at the home museum, and even then only rarely. In many cases it is difficult for scholars to gain access to select works because the works are in distant locales, or in storage, or have been lost or destroyed. In such cases, high–quality digital images distributed electronically and viewed on–screen must suffice. Image capture has long been a central concern for imaging specialists, conservators, and restorers, but it is becoming ever more important for connoisseurs and art interpreters. As a result of these trends, there is a large and rapidly growing number of digital images of artworks available online and in digital repositories.

In December 2020 a nonspecialist paid $98,000US at auction for a private viewing of *Mona Lisa*.

Computers can process information only if it is in electronic (digital) form, and thus the first step in algorithmic analysis of two–dimensional art is the digital imaging of artworks. There are many devices, methods, and wavelengths for such image capture, each more or less appropriate to the extraction of particular information. For instance, analysis of pigments would rely on imaging with fine color resolution; a study of a painter's working methods would rely on infrared reflectography to reveal the pentimenti and underdrawings; a study of brush strokes would rely on methods to capture the three–dimensional shape of a painting's surface; and so forth. Even within a single imaging technique or modality, such as visible–light photography, the settings and specifications (spatial resolution, types of color filters, range of brightness sensitivity, etc.) will affect the final images and thus how we read and digitally process them.

We shall consider only *digital* imaging in its wide variety of implementations. The earlier era of (analog) silver–halide film and development is long over, and while we may occasionally deal with

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such legacy images, our focus is on the future, where every image is captured—or at least stored—digitally.

Archival digital image storage has long been less expensive and more reliable than the equivalent for hardcopy images, and these benefits become more compelling with every passing year. With careful archival management, digital files can, in theory, remain undegraded indefinitely; the case for hardcopies is not nearly as compelling. Digital files, properly archived, allow dissemination, display, search and—our central concern, algorithmic analysis—in ways prior and legacy storage media do not. It is for these and similar reasons art museums, galleries, and auction houses worldwide are scanning print photographs, x-rays, and other legacy art images to convert them into digital form. In the long run, all art images of every type will be in a digital format.[1]

[1] David G. Stork. From digital imaging to computer image analysis of fine art. In Fay Huang and Reen-Cheng Wang, editors, *Arts and Technology ArtsIT*, volume 30 of *Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pages 1–8. Springer, Berlin, Germany, 2010a

The technology of digital photography, digital image capture, and the more sophisticated methods we shall discuss are all rather technical, where imaging specialists debate subtleties and minutia. Our purpose here is neither to delve into such details nor to provide a "how to," but instead to inform art scholars and computer image analysts who will *use*, interpret, and algorithmically analyze digital images from these domains. Art scholars must understand key properties of the leading imaging methods used in art documentation and analysis, their strengths and weaknesses, what they can and cannot reveal about a work, so these scholars can best develop image algorithms for particular studies.

We begin in Section 1.2 by reviewing the basic physics of electromagnetic radiation, primarily x-radiation, ultraviolet, visible light, and infrared. Then we turn in Section 1.3 to the interactions of such radiation and art materials, to see what information about artworks each type of radiation, and thus imaging method, can and cannot provide. Next, in Section 1.4, we turn to the functions of cameras and scanners, which provide the visible–light images that have proven most useful in computational art analysis.

We consider more closely, in Section 1.5, the spectral aspects of imaging as well as the specifications such as spatial resolution, dynamic range, bit depth, and color gamut. We discuss the presentation and reading of images on–screen in Section 1.6. Then, in Sections 1.7 and 1.8, we discuss ultraviolet and infrared imaging. These modalities capture information invisible to the human eye and can reveal a great deal about artworks, including their hidden layers, properties of pigments, supports, and more.

While traditional digital cameras capture component images using just three ranges of color sensitivity (red, green, and blue)—so-called *multispectral imaging*—in *hyperspectral imaging*, we capture 10, 20, or even as many as 50 such images, each covering a different range of wavelengths. Often these ranges extend from ultraviolet, through visible, to infrared, and preferably are equally spaced in wavelength, as we discuss in Section 1.9. Hyperspectral information is typically far richer than that available in any single wavelength range, and enables a number of techniques, such as mapping pigments throughout a painting. X-ray imaging has proven extremely valuable in the study of artworks, particularly paintings, because of its high penetration power; x-ray images often reveal the early stages of an artwork, where an artist is experimenting and developing the work, as we shall see in Section 1.10.

Most of the above imaging methods are *passive*, where we illuminate the artwork and capture an image based on the reflected or transmitted light. The other major class of imaging comprises the so-called *active* methods, most notably *fluorescence imaging*, in which we illuminate the artwork and through atomic and molecular processes it then "glows" or fluoresces, emitting electromagnetic radiation of a different wavelength, as we discuss in Section 1.11.

The surfaces of nearly all two–dimensional artworks such as paintings have texture and depth—that is, they are three–dimensional, like a microscopic version of the topography of a mountainous landscape. Thus, in Section 1.12 we consider methods for capturing this three–dimensional shape—the *depth map*—of "flat" artworks. We consider two general methods based on capturing multiple images—either from different directions with constant illumination, or from one direction but under *illumination* from different directions. The latter technique is the basis of reflectance transformation imaging (RTI).

Then, in Section 1.13, we discuss optical coherence tomography (OCT), a rather sophisticated method for imaging the three–dimensional structure of layers *beneath* the pigment surface of a painting. Although such information has yet to be addressed by computer image analysis of the sort we discuss throughout this book, such information has shown value in authentication studies.

We end in Section 1.14 with a short discussion of nondestructive Raman spectroscopic imaging (RSI) and X-ray fluorescence imaging (XRF), which reveal information about molecules and atomic elements throughout a painting. Such information has two primary uses in art scholarship: revealing the likely pigments used in an artwork, and imaging hidden layers of paints.

1.2 Electromagnetic radiation and light

Light—and more generally electromagnetic radiation—is essential for us to see and otherwise sense artworks such as paintings, drawings, and prints. The artworks that command our efforts are physical objects, made of paper, cotton canvas, media (such as oil or acrylic paint, pencil, or charcoal), and we need electromagnetic radiation to capture images of artworks and then put it into digital form for computer analysis.

In broad overview, during imaging radiation passes from a source or illuminator, then reflects from the artwork back to a detector, such as our eye, camera, or other sensor. X-radiation is high–energy electromagnetic radiation that passes *through* most materials but is stopped by heavy atoms such as Lead, Iron, and Cadmium. Thus x-ray imaging relies on sensors *behind* the artwork and captures a form of shadow, much as does medical x-ray imaging of bones and teeth.

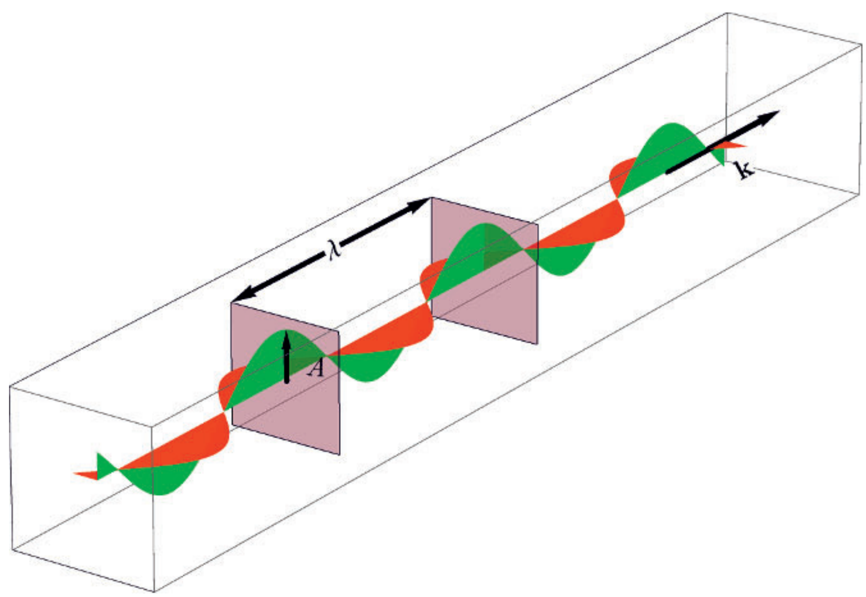

Figure 1.1: A ray of electromagnetic radiation is an oscillating wave of an electric field (green), which may lie in a plane; if so, a magnetic field (red) lies in the perpendicular plane. The smallest separation between parts of the wave that have the same shape, such as peaks, is the *wavelength*, λ. The *magnitude* of the electric field is described by the wave's amplitude, A. The direction of the wave is represented by the *wave vector*, $\mathbf{k}$, which points in the direction of wave propagation and is of magnitude $|\mathbf{k}| = 2\pi/\lambda$.

Figure 1.1 shows schematically a ray of electromagnetic radiation, for example visible light. Such radiation is a propagating disturbance in an electric field, analogous to a wave traveling down a rope or to a water wave. An electric field describes a fundamental physical condition underlying the attraction and repulsion of electrically charged particles. Such a field interacts with the material in an artwork by exerting forces on charged particles—primarily electrons—in the material, such as pigments and supports, as described in Section 1.3.

All electromagnetic waves propagate at the same speed in a vacuum, denoted c, but more slowly in media such as glass, plastic, or varnish. An electromagnetic wave can be characterized by its *wavelength*, λ ("lambda"), the distance between successive peaks of the wave; its *frequency*, ν ("nu"), the number of wavelengths that pass a particular point each second; and its *magnitude* or *amplitude*, A, a measure of the energy carried by the radiation and hence the force the wave can exert on charged particles. Another property of a wave is its *direction* of propagation, which we represent by the *wave vector*, $\mathbf{k}$, whose direction is the same as that of propagation and of magnitude (length) $|\mathbf{k}| = 2\pi/\lambda$. Here $|\mathbf{k}|$ is called the *wave number* and has units of cm^{-1}, read as "inverse centimeters." Thus, the larger the magnitude of the wave vector (the longer that vector and the larger the wave number), the shorter the wavelength of the radiation, and vice versa. This convention is based on the fact that the shorter the wavelength the greater the energy in an electromagnetic wave.

Latin: "celer," swift, fast.

The two complementary representations of such a propagating disturbance are as a *wave* and as a *ray* (or *beam*), each useful in different circumstances. When we discuss the physics of light interacting with materials such as pigments, then light's properties of wavelength and amplitude are most relevant; its spatial extent and sometimes even direction of propagation are of ancillary importance. If instead we are studying the reflection of light from a smooth surface, or its focusing through a lens, then its *direction* is of primary importance, so we represent light as an idealized thin ray propagating in a direction represented by $\mathbf{k}$.

There are other properties of such waves, for instance polarization, which describes the direction of the electric field variations with respect to the direction of propagation, $\mathbf{k}$.

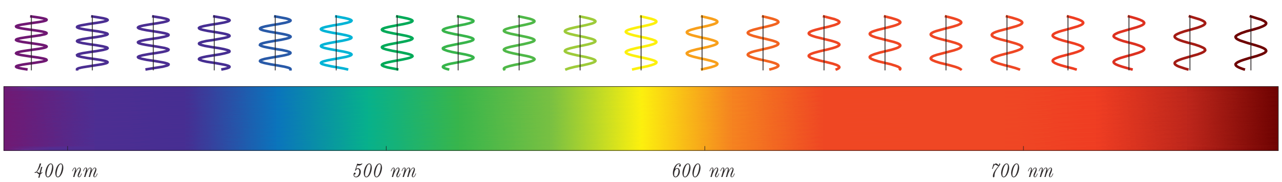

Figure 1.2: Electromagnetic waves and the continuous spectrum from near ultraviolet to near infrared. (Of course the waves themselves are not colored; instead they induce the psychological perception of a given color in normal-sighted humans.) At the scale of the waves printed on this page, the width of a typical human hair would be about twice the height of this printed page.

Electromagnetic waves interact with materials in ways that depend upon the wavelength, and it is convenient to refer to ranges of wavelengths by the nature of such interactions and the technologies of detection. The central concern in art imaging is the *visible* range, which is typically considered to be 400–700 *nm* (though many normal–sighted people can sense light of wavelengths as short as 380 *nm*). Light of shorter wavelengths within this range leads to the perception of blue or violet, while light of longer wavelengths leads to the perception of red. Figure 1.2 shows the continuous visible spectrum along with schematic plots of the undulations in the electric field themselves.

One nanometer (*nm*) is 10^{-9} *m*.