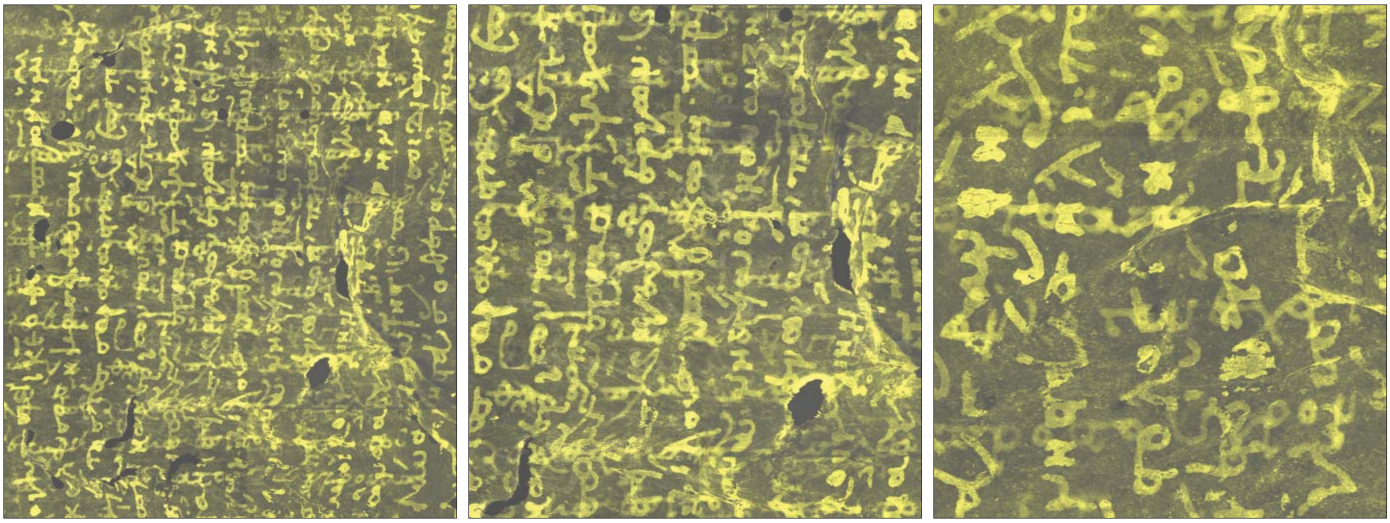


The Owner of the Archimedes Palimpsest

Archimedes brought to light

Uwe Bergmann describes how physicists have used X-ray fluorescence to uncover some of Archimedes' oldest writings that were hidden from sight in an ancient medieval prayer book

Just over 100 years ago in the summer of 1906, a Danish scholar called Johan Ludvig Heiberg travelled to the famous Metochion library of the Church of the Holy Sepulcher in Constantinople. He had got wind of an intriguing medieval prayer book that had recently been found at the library, and which contained a series of Christian prayers written on parchment recycled from older books. But underneath the scrawlings of a 13th-century medieval monk, the battered manuscript also appeared to contain some strange Greek writing as well as mysterious drawings and mathematical symbols. When Heiberg saw the book, he soon realized that the hidden material in fact contained the thoughts of Archimedes of Syracuse (287–212 BC) – one of the greatest thinkers of the ancient world.

Heiberg's discovery was headline news around the world, with the story even appearing on the front page of the *New York Times* on 16 July 1907. The script hidden under the medieval prayers was not written by Archimedes himself; sadly none of his own handwritten texts survive. However, it does contain seven of Archimedes' treatises, including the only surviving copy of *On Floating Bodies* in its original Greek, plus two other treatises – *The Method of Mechanical Theorems* and the *Stomachion* – that had never been seen before in Greek or any other language. Scribes had made the first copy of Archimedes' texts not long after he died and it is believed that the manuscript, which was written in about AD 950, is only about the fifth copy of his original writing.

Having photographed the pages and transcribed as well as he could the text that lay obscured, Heiberg used the manuscript to create an entirely new edition of the complete works of Archimedes, which he published between 1910 and 1915. However, Heiberg was not able to read all of the hidden text in the prayer book. Worse was to come when the book – for reasons that we still do not know – disappeared after it was removed from the library in 1908.

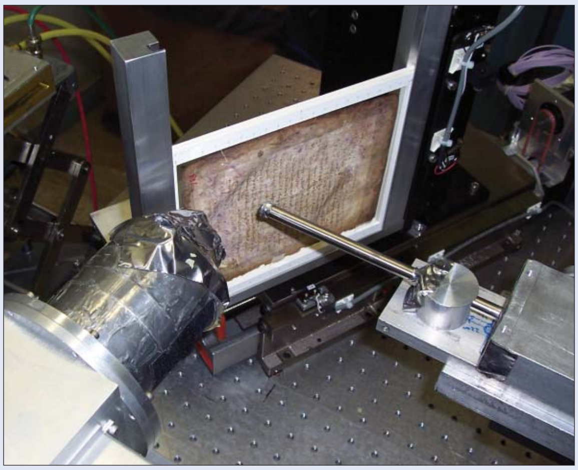
It did not resurface for another 90 years, when it was put up for auction at Christie's in New York on 28 October 1998, advertised as being from a private French collection. The book had, however, suffered greatly in the intervening decades. Some pages that Heiberg had transcribed were now missing. The book had also been attacked by mould, which had damaged some of the text to the point where it could no longer be seen by eye. Most extraordinarily of all, four pages of the book contained paintings of religious scenes that had been added – perhaps to make the book seem more valuable as a medieval manuscript – on top of the prayer-book text and therefore over the top of Archimedes' texts beneath that. (We now know that these images were created some time after 1929 as they were copied from a publication of that year.)

Fortunately, the anonymous new owner of the manuscript, who paid $2m to the book's French owners plus an extra 10% to Christies, subsequently agreed to lend it to the Walters Art Museum in Baltimore, US, where the delicate manuscript was carefully and painstakingly unbound. The leaves, which had deteriorated greatly since Heiberg had seen them almost a century before, were then imaged by a team led by the physicist Roger Easton from the Rochester Institute of Technology in the US. The researchers used a technique known as multispectral imaging, which involved exposing individual pages of the book to visible and ultraviolet light of various wavelengths. Since the ink, the parchment and the hidden text reflect these wavelengths to different extents, Easton and his colleagues – using a series of

Uwe Bergmann is a physicist at the Stanford Linear Accelerator Center (SLAC) in California, US, e-mail bergmann@slac.stanford.edu

Hidden thoughts
The Archimedes Palimpsest was originally written in AD 950 before the text was erased and the paper reused by a monk in 1229 to produce a Christian prayer book.

1 Under exposure



SLAC

A leaf of the Archimedes Palimpsest exposed to X-rays from the Stanford Synchrotron Radiation Facility in the US. The leaf moves on a stage so that the beam scans across the text, line by line. The detector, which is covered in lead and placed at 90 degrees to the incoming beam, measures the X-ray fluorescent photons emitted by atoms in the paper.

algorithms to analyse the reflected light – were able to reveal most of Archimedes' writings in the manuscript, including numerous passages that Heiberg himself could not see by eye.

However, significant sections of some of Archimedes' most important works could not be revealed using this technique. In particular, Easton and colleagues could not make out much of the text that was hidden on the four pages containing the forged 20th-century paintings. Over the last two years, however, my colleagues and I at the Stanford Linear Accelerator Center (SLAC) in California have been able to use a different technique, known as X-ray fluorescence, to reveal the hidden text on these pages and to expose several passages that had never been seen before. This new information has revealed the name of the monk – Johannes Myronas – who dedicated the prayer book and the date on which he did so – 14 April 1229. More importantly, it has also helped historians to gain new insights into Archimedes himself (see box below).

X-ray fluorescence

The mould-stained prayer book at the centre of this story consists of parchment leaves that had been recycled from five older books. After scraping off the old purple-black "gall" ink – an iron-based pigment that was widely used for drawing and writing in medieval Europe – Myronas then probably used lemon juice to partly erase Archimedes' original writings before rotating the unbound leaves by 90 degrees and writing on top of them. He then rebound these leaves to create the book we know today, which is called the Archimedes Palimpsest (from the Greek word *palimpsestos* for "scraped again").

It should come as no surprise to physicists that X-rays, which are widely used in medicine to "see" through matter, should be able to reveal the hidden text. When X-rays are shone on a material, individual photons can either pass through it unhindered, scatter elastically or inelastically, or get absorbed. Unfortunately, we cannot examine very thin objects – such as traces of faint ink on a manuscript – simply by measuring the amount of transmitted light, as we would with a standard chest or dental X-ray image, where light and dark regions indicate areas of low and high absorption. The problem is that the difference in absorption between, say, an area on a page of the manuscript with ink and an area without would be overwhelmed by statistical fluctuations in the very large transmitted signal.

X-ray fluorescence (XRF) overcomes this problem in a simple but effective way. When a material is exposed to X-rays, the radiation can occasionally ionize it by knocking out an electron orbiting the nucleus in one of the inner shells. If this happens, an electron from a higher-energy outer shell immediately takes its place, emitting a secondary X-ray fluorescence photon as it does so. The energy of this photon is a unique fingerprint of each element in the material, which means that the distribution of a particular element, such as iron or calcium, can be obtained by scanning an X-ray beam across a sample and simply tuning the detector to the required energy. (X-ray fluorescent photons are of course also created in standard medical X-ray imaging – it is just that we usually do not bother to measure them.) Moreover, because the secondary

Infinitely influential

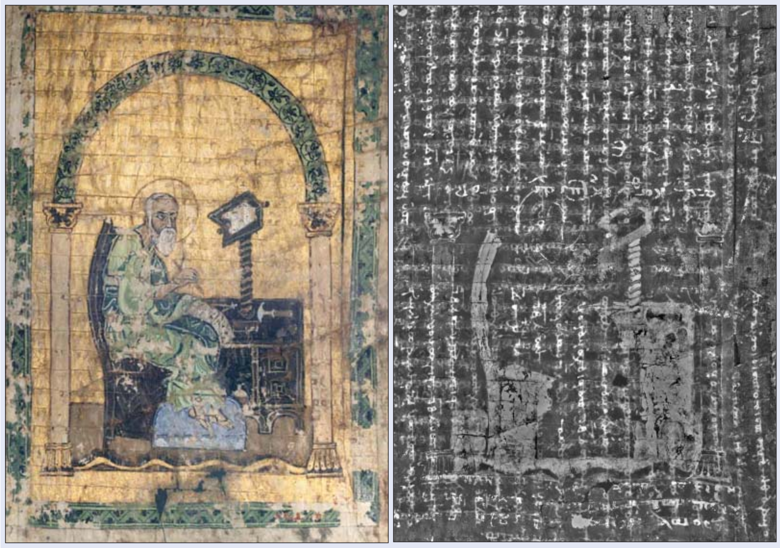
The first contribution by Archimedes to the growth of physics was to develop the essential tool of an abstract mathematical system. Instead of dealing with the complexities of many interacting forces in a messy environment, he chose to consider an ideal situation with few objects (ideally one) acting under the influence of a single force. Under such conditions, Archimedes showed that, with very few assumptions, one can deduce the laws of the balance and of buoyancy, and then use them to find the centres of gravity of various shapes and finally to predict the stability or otherwise of various objects immersed in a liquid. While the results themselves were seminal (in particular, the concept of a centre of gravity would be crucial for all later physics), Archimedes' major contribution was to inspire future mathematical modelling of physical systems.

The key technique is to treat physical objects as if they are geometrical objects in Euclidean space. However, this gives rise to problems of continuity: is a physical body made of infinitely many planes? In other words, one soon needs the integral – and this is where Archimedes' second contribution to the growth of physics comes in. Archimedes developed in rich detail a technique that is essentially equivalent to modern limits. Curvilinear objects such as spirals or parabolas can be bounded by a series of rectilinear objects whose difference from the curvilinear object he showed to be smaller than any given amount. Archimedes' approach differed from calculus because it was not systematic but treated each case individually, for example constructing a special series for spiral areas or for parabolas. However, Archimedes' work served in this respect, once again, as inspiration: modern scientists developed calculus as an attempt to emulate – and then to go one better than – Archimedes himself.

photons are emitted in all directions, the very large transmitted X-ray signal can be eliminated by placing the detector at right angles to the beam.

XRF is routinely used at synchrotron-radiation facilities. These facilities are large circular devices that can be over a kilometre in circumference and around which electrons travel to within 10^{-6}% of the speed of light. As they do this, the electrons emit huge quantities of radiation. Long considered a nuisance by particle physicists, synchrotron radiation has proved so useful in other fields – from condensed-matter physics to biology – that there are now 60 or so dedicated synchrotron-radiation facilities around the world. The big advantage of using synchrotron radiation is that it can be channelled into very intense, narrow beams of different wavelengths. Moreover, the radiation is linearly polarized, which means that the scattered X-ray signal is almost zero at 90 degrees to the original beam direction. In the case of XRF, another advantage of placing the detector at the side of the beam is that it will therefore only measure the fluorescent signal, with much less contamination from the scattered photons than if it were placed at any other position.

2 Different light



The Owner of the Archimedes Palimpsest

A leaf (folio 57r) of the Palimpsest, covered with a forged painting from the 20th century, viewed in normal light (left). The other image of the same page, which was created by measuring the X-ray fluorescence from iron in the ink, reveals the Archimedes text (vertical) beneath the forgery.

The story unfolds

It was in November 2003, while on my way to a conference in Germany, that I first realized that the technique might help to uncover the hidden writings in the Archimedes Palimpsest. I had been reading an article in the German magazine *GEO* about the manuscript and, having previously used X-rays to detect metals in biological systems, realized that XRF could help to detect iron and other common elements in the ink. I immediately e-mailed Abigail Quandt, a conservator at the Walters Art Museum, who was part of a team that had been put in charge of the Archimedes manuscript. I was delighted to find that the team, led by her colleague William Noel, was looking for new ways to study this ancient book. Indeed, it turned out that two other researchers – Gene Hall from Rutgers University and Bob Morton from the oil firm ConocoPhillips – had also suggested using XRF imaging. Another team member – Johns Hopkins University physicist Bill Christens-Barry – had already been thinking of using X-rays too.

In March 2004 Hall and the team carried out the first tests on the Palimpsest using X-rays from a commercial generator. Although these tests were promising, the results confirmed my belief that synchrotron radiation could be much better because it would allow the book to be scanned much faster and with higher resolution. Indeed, I had already begun collaborating with my SLAC colleague Martin George, who helped to develop an XRF system that could image and scan the Palimpsest at high speed. It consisted of a computer-controlled stage that could hold a single leaf from the book and be moved from side to side so that the X-ray beam from SLAC's powerful SPEAR3 accelerator could be scanned across the sample (see figure 1). A 2D image of the page could then be built up by plotting the intensity of the fluorescent X-rays at a particular energy.

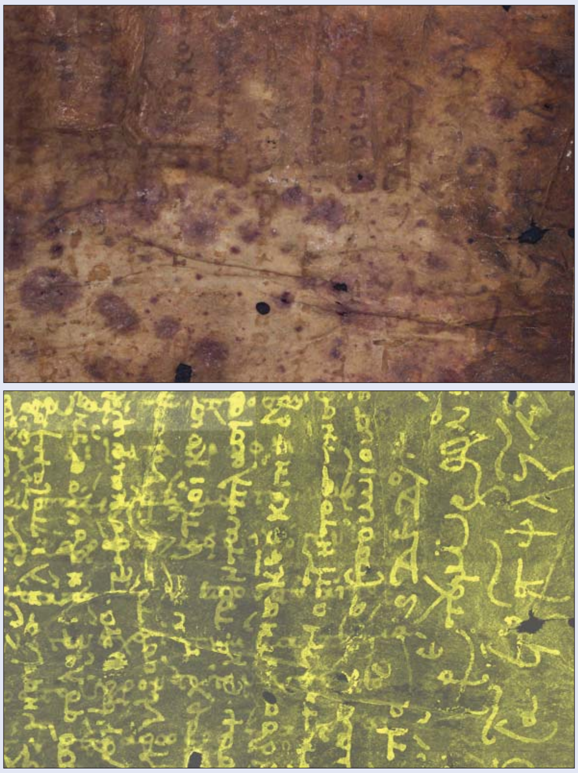
The problem with imaging a delicate object like the Palimpsest using intense beams of X-rays is that it can be damaged if exposed for too long. Working with Gregory Young from the Conservation Institute in Ottawa, Canada, we carried out tests on a piece of parch-

So far, I have said nothing about Archimedes the man. We know that he died with the fall of his native Sicilian city, Syracuse, in 212 BC – a fall that would have occurred sooner were it not for his success in applying ballistic engineering to develop weapons such as catapults. Beyond this we know little else about his life. His personality is clear, however, and comes through in his writings: innovative, always aiming to surprise, elegant and rigorous (in the most non-pedantic sense of the term). Many of his works survive. Some of these were known during the Renaissance, such as his famous geometrical measurements of circles and spheres, and his treatises on statics and hydrostatics. However, his work on hydrostatics, *On Floating Bodies*, was known only through a medieval Latin translation. It was only with the discovery of the Palimpsest in 1906 that *The Method* – the work in which Archimedes comes closest to modern calculus – came to light, as well as the Greek original of *On Floating Bodies* and an otherwise enigmatic fragment called the *Stomachion*.

Recently, new imaging techniques carried out at the Stanford Linear Accelerator Center and elsewhere (see main text) have allowed us to recover significantly more from the Palimpsest. For example, X-ray images have given us the Greek version of the final proposition from *On Floating Bodies*. More significantly, we now see that in *The Method* Archimedes was playing not just with potential infinity, but also with actual infinity, and was likely to be the first to ever do so. An X-ray image of one of the pages covered by a forged painting made crucial contributions to this very important finding. Some scholars have also suggested that the goal of the *Stomachion* was to contribute to "combinatorics" – the field of mathematics studying the number of ways in which a task may be accomplished.

Reviel Netz is a historian at Stanford University in California, US, e-mail reviel.netz@stanford.edu

3 New revelations



The Owner of the Archimedes Palimpsest

This folio, seen in normal light (top) and through its X-ray fluorescence signal from iron (bottom), contains text from the final proposition of Archimedes' treatise *On Floating Bodies* that had never been seen before in its original language (Greek). This text, which appears in horizontal lines, was written some time during the 10th century. The brighter writing, which appears in vertical columns, is by the monk who created the Palimpsest by scraping off the Greek text and writing Christian prayers on top. The two lines on the extreme right reveal that the monk was called Johannes Myronas and that he dedicated the prayer book on 14 April 1229.

ment from a will written in 1870 that had been given to us by Quandt at the Walters Art Museum from her private collection. We found that if the parchment is moved sufficiently quickly so that the beam dwells for no longer than 0.1 s on every area through which it is passing, then no measurable damage occurs to the document's fibres. The only snag was that when the beam reached the edges of a particular line of the document, the stage holding the individual pages had to stop briefly and step down to the next line – a process that could take as long as 1 s. To avoid overexposure during these stops, we added a fast pneumatic beam shutter to the computerized scanning system, which remained open only when the parchment was moving.

Our tests at SLAC proved so successful that we were able to persuade the Archimedes team to let us use our equipment on the real Palimpsest. The team arrived in May 2005 with three test pages (including one covered with a forged painting) and we were soon able to image half of one page at a resolution of 250 dots per centimetre in just 30 hours (*Nature* **435** 257). We then used algorithms developed by Keith Knox, a physicist from Boeing, to convert the raw data into 2D images.

Our findings in *The Method* have contributed to a new debate about Archimedes' concept of infinity

In all of our measurements we were most interested in the fluorescence from iron, which is the most common element in the ink. But by placing suitable electronic "windows" on the detector, we were able to simultaneously also record the signal from other elements, including calcium, zinc, barium and copper. The iron XRF image clearly revealed Archimedes' writing under one of the forged paintings that had been added in the 20th century and – in the next two runs during March and August last year – we were able to scan various texts that could not be revealed with other techniques as well as some writings that do not appear anywhere else. By installing better detectors and by including a new read-out system that had been developed by our colleague Alex Garachtchenko, we can now scan a whole page in just 12 hours with the X-ray beam sweeping over each 40 μm^2 area of the sample in just 3 ms.

In particular, we have been able to uncover part of *The Method*, Archimedes' most advanced treatise, hidden under one of the forgeries (figure 2), as well as writings from the final (and most elaborate) proposition of *On Floating Bodies* (figure 3). Even Heiberg, who did not have to deal with the additional problem of the forged paintings, could not read these texts. We now know that this original Greek version of *On Floating Bodies* contains several significant differences to the familiar Latin translation, including a different arrangement of diagrams. Meanwhile, our findings in *The Method* have contributed to a new debate about Archimedes' concept of infinity.

The cycle closes

So far about 20 pages of the Palimpsest have been scanned using the X-ray beam from SLAC's SPEAR3 accelerator. In most cases, the best XRF images came from the iron in the ink, but we have also obtained images using data from several other elements too. To our surprise, a previously partly unidentified drawing from *The Method* appeared in the calcium but not the iron signal (2006 *Science* **313** 744). We believe this was caused by chalk from the parchment that had collected in the grooves created by the scribe's nib, while the iron had been washed out. The calcium image was also particularly useful for some areas beneath the forged pages, where the 20th-century paint contained so much iron that it swamped the iron signal from the ancient writings.

Unfortunately, this was not the case for all of these areas, some small parts of which have still not been revealed. Next year the Archimedes team plans to return to SLAC again to image some of the badly damaged areas of those pages of the Palimpsest containing Archimedes' discussion of the mathematics of the *Stomachion* – a puzzle containing 14 pieces that can be made to form a square. My colleague Reviel Netz, a historian at Stanford University, is hopeful that these XRF images will fill in the missing passages of this important text.

As we now know, Archimedes was one of the true fathers and earliest practitioners of physics. In a fascinating cycle spanning more than two millennia, it is fitting that one of the most advanced tools of modern physics – the particle accelerator – should make such a big contribution to our understanding of this genius from ancient Greece who had so significant an impact on modern science.