Archaeometry – an example of interdisciplinarity in engineering education

L. Musílek
Professor
Czech Technical University in Prague
Prague, Czech Republic
musilek@fjfi.cvut.cz

Keywords: Interdisciplinarity, engineering education, archaeometry

INTRODUCTION

Archaeometry is the application of techniques used in natural sciences and engineering for investigations of various archaeological finds, and, in the wider sense of the word, also of pieces of fine and applied arts, historical buildings, etc. The two key areas of activities are a) dating and b) analysing archaeological materials and materials of objects of cultural heritage. However, also investigations of internal structure and material layers of various artefacts can be considered as an integral part of this branch of science.

More than a hundred years since the earliest use of scientific methods for a deeper understanding of culture from the past, archaeometry has developed into a discipline that links physics, chemistry, biology, information sciences and construction of instrumentation with historical and archaeological studies (in the sense of cultural history). Therefore, it requires close collaboration among specialists from all these disciplines. This means that it can be included not only into the curricula of universities dealing with humanities, with departments specialised to archaeology or history of art, but also into the curricula of universities dealing with applied sciences and engineering. Of course, it will never be a dominant subject of study, a part of the basic course of history and archaeology at social sciences or of physics and chemistry at engineering faculties. However, it is well justified at least as an optional course at any level of studies, taking into consideration that profundity of explanation must be adjusted to the previous experience and knowledge of students.

The curricula of engineering faculties are usually heavily loaded with courses in mathematics and physics and sometimes also in chemistry. This is fully understandable, as engineering disciplines are based on these exact sciences. Excursions into interesting interdisciplinary applications can help students to extend their perception of world as a multifaceted complex of human knowledge and to appreciate that mathematics, physics and chemistry are not only dry sciences, but that they can have very colourful outputs. Archaeometry can represent such refreshing wind in the demanding curriculum, not because it is easier and less demanding, but because it can give some insight into areas considered to be far from exact sciences and extend cultural awareness of students.

1 ARCHAEOMETRY AS A SCIENTIFIC DISCIPLINE

As stated above, two main goals of archaeometry are to date various artefacts and archaeological finds (see, e.g. [1]) and to analyse the materials of various objects of cultural and historic importance (e.g. [2]). Analytical techniques used in archaeometry are based on physical and chemical principles, which are general, and they can be used for any material analysis in industry, agriculture and food production, in various fields of research, etc. Dating methods, such as radiocarbon or thermoluminescence dating, are specific for archaeometry, though they have close relations to some other scientific disciplines (in the case of the two methods named here as examples, they are linked to natural radioactivity, radiation effects and detection, nuclear instrumentation and statistical processing of results).

1.1 Example 1: X-ray fluorescence analysis

Let us demonstrate the multidisciplinarity of archaeometric investigations in two examples of frequently used methods, X-ray fluorescence analysis as an analytical method and radiocarbon dating as a method of age determination.

X-ray fluorescence analysis is based on fact, expressed by the Moseley’s law, published in1913, that excited atoms emit X-rays with exactly defined energy, which increases with increasing proton numbers of these atoms. Emitted characteristic radiations can therefore serve for identification of chemical elements – energy of a characteristic line for qualitative determination of presence of a particular element and its intensity for quantitative determination of its amount.

The whole procedure of analysis therefore consists of excitation of atoms of an investigated material by ionising radiation (soft gamma from radionuclides, X-rays from X-ray tubes, electrons, protons or other charged particles), spectrometry of excited characteristic X-rays (usually by a semiconductor spectrometer, sometimes by a wave-dispersive spectrometer based on the Bragg diffraction), analysis of detected spectra from the point of view of chemical elements present in the analysed material and quantification of their concentration, and evaluation of possible sources of uncertainties. Calibration of the measuring system is also the necessary part of the whole procedure. All these steps are in the border area between engineering and natural sciences and should be a domain of graduates from engineering and exact sciences. However, questions must be initially laid down by archaeologists, art historians or restorers of an investigated artefact. What are we looking for, what information can be obtained, if we better know the composition of materials, will this information be relevant for the history of an artefact or for its restoration? This, of course, is not a matter of engineers. And interpretation of results, attributing the object of investigation into correct historical context, must be also done by specialists in archaeology or art history.

X-ray fluorescence analysis is the method, which is non-invasive and non-destructive and measurements can be carried out in situ. This means that it is very universal and can be used for solving many problems connected with composition of materials, starting by pigments on old manuscripts, paintings and frescos, through pottery, metals and solders at sculptures or products of applied arts, and finishing by marble, building stones, etc. A lot of examples can be found, e.g., in [3]. This wide variety of applications also demands for adequate engineering skills, as it is necessary to select and design the optimum version of the method and instrumentation, and to determine in dialogue with a collaborator from soft sciences, what should and what can be measured and which results can be expected, what are the limits of application of particular methods for solving the given problem.

1.2 Example 2: Radiocarbon dating

Radiocarbon dating has become a synonym for archaeological dating as a whole for general public, but this is not a true image, many other methods are in use or investigation. However, radiocarbon dating is a frequently used method for determining the age of objects of organic origin, which has brought many interesting results. Similarly as many methods in archaeometry, it is based on principles of physics and engineering, in this case also with important contribution of chemistry (Prof. Willard F. Libby, inventor of radiocarbon dating, was awarded by Nobel prize for chemistry in 1960). The method is based on the continuous production of radioactive isotope of carbon ^{14}C in the earth atmosphere by nuclear reaction of secondary neutrons in cosmic rays with atmospheric nitrogen. This radioactive carbon is absorbed by living plants and animals and the equilibrium concentration of the radioactive isotope in relation to the stable isotopes of carbon is established during their life. When the living organism dies, exchange of carbon with the environment stops and activity of ^{14}C in the investigated object decreases by its radioactive decay. The time, which has passed from the death of this particular organism, can be determined from the ratio of radioactive carbon to its stable isotopes. Therefore, any ancient materials of organic origin can be dated approximately up to the age of 50 000 years (this range is given by the half-life of ^{14}C, which is 5730 years). In this part of the method, its principle is a mixture of physics, biology and environmental sciences.

^{14}C is a relatively low energy beta radiation source and its activity (or number of nuclei) in the dated samples is very low. This means that the samples for measurement must be very carefully processed and carbon must be quantitatively separated. There are two methods of determining the amount of ^{14}C in the sample, the older one – counting of radioactive decays in a low background beta detector, and the newer one – direct counting of nuclei from the sample by accelerator mass spectrometry. Processing of samples for these two versions of the method is different, but it is always a very demanding chemical procedure.

And now a few words about the contribution of engineering: Detection of beta decays of ^{14}C is not easy because of a low range of emitted electrons and a low frequency of events. This demands for the sophisticated construction of the detector with low background of counts from “parasitic” radiation emitted by natural radioisotopes in materials surrounding the sensitive volume of the detector and from cosmic radiation. Construction and optimisation of such detector and its shielding is a very good piece of engineering work. Concerning the other method of detection, i.e., accelerator mass spectrometry, building of an accelerator laboratory, most often with a tandem linear accelerator, is even more sophisticated (and also expensive) engineering job. However, it should be said that such laboratory is usually a multi-purpose installation and that radiocarbon dating is only a part of its programme. In all cases, processing of results and estimating uncertainties and possible errors is the further part of work of engineering character.

Finally, the results must be interpreted in the archaeological or historical context. This is a part of the whole investigation, which belongs to specialists in archaeology or history of art, not to physicists, chemists or engineers.

1.3 General situation

As follows from the examples in paragraphs 1.1 and 1.2, methods used in archaeometry are in the border area between few scientific disciplines and connect characteristic features of both hard and soft sciences. Any method, which is used, can be analysed by a similar way and it can be shown that it mixes scientific approaches of very different branches of science, from mathematics on the one pole to humanities on the other pole. Multidisciplinary teams are needed, in which engineers, physicists and chemists should understand the demands of archaeologists and art historians and, vice versa, archaeologists and art historians should understand the possibilities, advances and limits of methods based on exact sciences. This multidisciplinarity needs to be projected also to education programmes at technical universities and other engineering schools. Archaeometry is only one of such examples, maybe nice and attractive one, but the same situation and the same need of collaboration of specialists from many different branches of science and preparing students for such collaboration exists nowadays in many scientific areas (medical physics, environmental sciences, biophysics and biochemistry, etc.).

2 APPROACH TO ARCHAEOMETRY AT A TECHNICAL UNIVERSITY

2.1 Preconditions required from students

There is very different, what can be expected from students and what should be included into lectures, if the subject is taught at the bachelor, master or doctoral level. Archaeometry is an exact science and a deep view into its methods needs understanding many specific topics in mathematics, physics, chemistry, information sciences and data processing. Such knowledge cannot be expected at students in bachelor courses. They have a general overview of these disciplines at the level, which results from high school programmes and introductory university courses. Therefore, conception of the subject must be also more general and some basic information non-specific for archaeometric methods needs to be included. The aim of such topic in the study programme cannot be the deep insight into this branch, but awakening an interest on application of scientific methods, showing that “dry” mathematics, physics and chemistry have very fruitful consequences in areas apparently far from hard sciences and engineering.

Situation is different, when this subject is included in a master programme. Complete knowledge of mathematics and processing results of measurements, including estimates of error, which is needed for archaeometry, can be expected as the precondition for the course. In physics, some understanding of specialised branches of this science, as. e.g., solid state physics, atomic and nuclear physics, electronics, detection of various kinds of radiation, evaluation of measurements, analytical methods, etc., is obvious at least at universities of the research type. Students usually have also some their own experimental experience, at least in model practical exercises. Much deeper insight into specific features of these methods is possible in this case, allowing not to deal with basic general principles (students know them from the previous courses), but to turn to details, which can be useful even after graduation, in case that the graduate will take job in this branch. This can be also reflected in the assignment of theses, deeply oriented to a particular archaeometric method. However, such theses usually ask for close collaboration with some archaeometric laboratory and for a consultant of the thesis well acquainted with the wide context of the problem, not only from the point of view of exact sciences, but also from humanities.

2.2 Example of content

Let us show the possible content of the one-semester lecture on methods of exact sciences in investigations of cultural heritage of mankind. The introduction should explain, what archaeometry is, say something about its history, areas of investigations and goals. Then two approaches to the subject are possible. One of them is structuring the explanation according to objects, which should be investigated (e.g., paintings, pottery, metallic objects, stone, buildings, etc.). However, this approach can be used only for advanced students, who are familiar with the principles of methods used. The other approach, more universal, is based on scientific methods and techniques of measurement and processing the results, and various applications are included as examples of possibilities given by a particular method. We will keep this approach in our further explanation, and we keep it also in the lectures at our university.

As mentioned above, the methods of archaeometry can be grouped into three main areas: methods for determining age of artefacts and materials, methods for analysing materials of artefacts (sometimes with possible interpretation leading to determining the geographic origin of the investigated object or its material or determining the ancient trade routes and connections), and methods probing the internal structure of objects. These topics must be reflected in various parts of the lecture. Sometimes also large area surveys searching for remainders of ancient civilisations are included into archaeometry. These areas of interest define the structure of the lecture.

There is a lot of dating methods of different importance, which have been developed during the history of this discipline (see, e.g., [1]). Only selection of the most important ones can therefore be presented in roughly thirty hours of a one-semestral lecture. First of all, radiocarbon dating must be included, being the most popular in general public. This is usually the only one dating method known to some extent to students. Other important and non-negligible methods, which should be included into the lectures, are dendrochronology and the complex of three mutually related methods based on measurements of accumulated doses from natural radiation in the dated object – i.e., thermoluminescence, optically stimulated luminescence and electron spin resonance. Selection of further methods may depend to some extent on the interests of a lecturer, e.g., archaeomagnetism or some methods based on decay of long living natural radionuclides (potassium – argon, natural decay series, etc.) can be included. Interesting examples of using these methods should be an integral part of explanation, as, e.g., the radiocarbon dating and the other tests of the famous Shroud of Turin [4]. Discussions about its (non)authenticity can also serve as illustration of the wider societal and ideological context of exact sciences and engineering.

The variety of analytical methods is even wider than the variety of dating methods. Many of them are based on interactions of electromagnetic radiation with various wave lengths (from infrared to X-rays) with material. All this spectrum of methods should be presented to students, with maximum emphasis to atomic emission spectrometry, atomic absorption spectrometry and X-ray fluorescence spectrometry as the most frequently used methods. However, it is not possible to limit the explanation to this group of methods. At least activation analysis, Raman microscopy, various modifications of mass spectrometry (inductively coupled plasma, accelerator mass spectrometry) and traditional metallography and petrography should also be mentioned. Plenty of interesting applications of analytical methods to objects of cultural heritage was published and can supplement the explanation. Let us mention at least one of them, which is not very typical, but has quite high impact to our historic knowledge: analysis of the wrought iron from the hull of the USS Monitor, known from the American Civil War, which showed surprisingly low quality of the material used and which gave evidence that engineer Ericsson and his co-workers constructing this warship were limited in selection of iron by conditions of the war industry [5].

Radiography (gamma, X-ray and neutron) is another area of interest. In fact these methods are as old as the discovery of X-rays by W.C. Roentgen (1895). The very first use of X-ray radiography, roentgenogram of the hand of Mrs. Roentgen, started medical applications, but W. Koenig tried to use this new radiation also for identification of overpainting on pictures as early as three months after publication of Roentgen's discovery. Moreover, industrial tomography applied to pieces of art, especially sculptures, extended later substantially possibilities of such investigations. Therefore, this group of methods should also be covered by the lecture.

This is the main frame of the lecture on archaeometry, covering the most frequently used methods. However, there is a lot of related methods, which can be added for investigations of some types of objects. This is, e.g., a survey of large areas, often from air or even by evaluation of satellite photos, for search of places of buried ancient settlements, photogrammetry for examination of detailed proportions of historical buildings and their parts (e.g., vaults) and for large sculptural complexes, the growing field of paleobiology, etc. Therefore, there is a lot of opportunities, how to extend the scope of the subject taught in the direction to other disciplines.

2.3 Practical exercises and problem solving

No area of knowledge can be fully understood only on the basis of lectures. Students should be engaged in the problems also by their own activity. What is possible in the field of archaeometry? The first step to deeper understanding of possibilities, which the methods of exact sciences and engineering bring to extending the cognition of monuments of art and archaeological finds, can be carried out in discussions with students about possibilities and methods of investigation of some typical artefacts. The difficulty can arise from the fact, that some artefacts have very high historical and artistic value, however such objects can be simulated by cheaper modern copies and imitations, sometimes even sold as souvenirs. Students understand that it is impossible to bring the object with price of tens thousands Euro or more into the seminar room.

To show an example, students can propose the methods, as complex as possible, of investigation of the inlaid wooden Turkish box, accompanied by the story that this is the war trophy from the camp of the grand vizier Kara Mustafa, when he was defeated in 1683 in the battle at Vienna. Students must find the proper methods, how to confirm or throw over the believability of this story, to summarize, what can be recognized from the point of view of various materials used on the box, which instrumentation is needed for such measurements, to consider possible uncertainties and errors in interpretation of the results, etc.

The higher level of practical training is a practical exercise – a simple experiment carried out by a student. Possibility of such practical exercises is to some extent limited by very high value of some objects of art, but also by very expensive and sophisticated instrumentation needed for applying some methods (research nuclear reactor as a source of neutrons for activation analysis, charged particle accelerator for accelerator mass spectrometry, etc.). Selection of practical exercises available for students depends strongly on the equipment at the university and on possible collaboration with external laboratories. However, there are some methods, which do not need too sophisticated equipment and can be included into practical education at most universities. .E.g., practically every university with a department dealing with ionising radiation is equipped by gamma and X-ray spectrometry and can carry out the X-ray fluorescence analysis of coins or similar small objects. Such university usually also have some X-ray machines and can prepare some exercises on X-ray radiography or, in the even better case, on more sophisticated tomographic measurements.

Semestral works and theses on the master or doctoral level need complex multidisciplinary approach. To avoid an intellectual exercise non-anchored in reality and to solve an actual practical problem, intensive collaboration with some department of archaeology, history of art, museum or similar institution is needed, as specialists in these topics must define the problem and supply the real objects to be investigated, and must help with interpretation of the results in the context of history.

2.4 Archaeometry at the CTU FNSPE

The lecture dealing with archaeometry and investigation of cultural heritage (called for better understanding “Methods of exact sciences in monument research”) is a one-semestral lecture, 2 hours per week, which means that the total time devoted to this subject is 28 to 30 hours (depending on occurrence of some state holiday during the semester). It is an optional lecture offered to all students at the Faculty, however, it has main relevance for students of the branches “Dosimetry and application of ionising radiation” and “Nuclear chemistry”. Its concept is constructed such a way, that it needs only basic knowledge of physics and chemistry on the level of bachelor courses of engineering as precautions, and therefore it is comprehensible also to students in the first years of study. Due to the credit system, it must not be placed into some particular phase of studies. The subject has the value of two ECTS credits and it is finished by an exam.

There are no specific laboratory exercises accompanying exclusively this lecture. The reason is simple – as mentioned above, the instrumentation and techniques for some methods are too sophisticated and measurements last too long. Moreover, some objects of interest (old manuscripts, jewellery, paintings, sculptures) are too valuable to be subjects of students’ exercises. However, some methodically related tasks are included into so called “special practical exercises” in radiation physics and chemistry. Students can familiarise themselves with the practical aspects of, e.g., X-ray fluorescence analysis or measurement of thermoluminescence.

Ten to twenty students usually use the possibility to choose this subject every year. The experience with them is very good, they are always active in the discussions about the topics taught in the particular lecture, which follows after the lecture, and their knowledge during the exam is usually also very good.

3 SUMMARY

Archaeometry is the scientific discipline, which is relatively new. Its usefulness and contribution to the areas narrated during the long history of art and studies of ancient civilisations mostly by experts with “classical” education, connoisseurs, needed to be recognised against some conservativism usual in any branch of science, Nowadays, it is an established part of scientific activities, which uses a lot of knowledge and methods of hard sciences and engineering, and therefore it is a relevant discipline for technical universities and faculties of engineering or exact sciences. The example of teaching this subject given here reflects the experience at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague (we are educating physicists and engineers and not archaeologists and art historians, therefore we are oriented more to the technical aspects of the problem, but we must always emphasize that specialists in different branches of science need to collaborate for obtaining reliable results and interpreting them). It is possible to say, that including archaeometry into the programme has been well accepted by students. Except the educational value in one of the interesting multidisciplinary applications of mathematics, physics and chemistry, it brings also a non-negligible contribution to the cultural cognizance of students, at least of those, who are not very narrowly oriented to one branch of science and are interested on the wider context of intellectual richness of mankind.

REFERENCES

[1] Aitken M.J. (1990), Science-based Dating in Archaeology, Longman, London, UK.

[2] Pollard M. et al. (2007), Analytical Chemistry in Archaeology, Cambridge University Press, Cambridge, UK.

[3] Uda M., Demortier, G. and Nakai I. (Eds.) (2005), X-Rays for Archaeology, Springer, Dordrecht, The Netherlands, pp. 27-53.

[4] Damon P. E.; et al. (1989), Radiocarbon dating of the Shroud of Turin, Nature 337, pp. 611–615.

[5] Boesenberg, J.S. (2006), Wrought Iron from the USS Monitor: Mineralogy, Petrology and Metallography. Archaeometry 48, pp. 613-631.