CHAPTER 4

The Van Meegeren Art Forgeries

Martin Braun*

After the liberation of Belgium in World War II, the Dutch Field Security began its hunt for Nazi collaborators. They discovered, in the records of a firm which had sold numerous works of art to the Germans, the name of a banker who had acted as an intermediary in the sale to Goering of the painting '*Woman Taken in Adultery*' by the famed 17th-century Dutch painter Jan Vermeer. The banker in turn revealed that he was acting on behalf of a third-rate Dutch painter H. A. Van Meegeren, and on May 29, 1945, Van Meegeren was arrested on the charge of collaborating with the enemy. On July 12, 1945, Van Meegeren startled the world by announcing from his prison cell that he had never sold *Woman Taken in Adultery* to Goering. Moreover, he stated that this painting and the very famous and beautiful *Disciples at Emmaus*, as well as four other presumed Vermeers and two de Hooghs (another 17th-century Dutch painter) were his own works. Many people, thought that Van Meegeren was lying to save himself from the charge of treason. To prove his point, Van Meegeren began, while in prison, to forge the Vermeer painting *Jesus Amongst the Doctors* to demonstrate to the skeptics just how good a forger of Vermeer he really was. The work was nearly completed when Van Meegeren learned that a charge of forgery had been substituted for that of collaboration. He therefore refused to finish and age the painting in the hope that investigators would not uncover his secret of aging his forgeries. To settle the question, an international panel of distinguished chemists, physicists, and art historians was appointed to investigate the matter. The panel took x-rays of the paintings to determine whether other paintings were underneath them. In addition, they analyzed the pigments

* Department of Mathematics, Queens College, Flushing, NY 11367.

(coloring materials) used in the paint and examined the paintings for certain signs of age.

Van Meegeren was well aware of these methods. To avoid detection, he scraped the paint from old paintings that were not worth much just to get the canvas, and he tried to use pigments that Vermeer would have used. Van Meegeren also knew that old paint was extremely hard and impossible to dissolve. Therefore, he cleverly mixed a chemical (phenoformaldehyde) into his paint, and this hardened into Bakelite when the finished painting was heated in an oven.

However, Van Meegeren was careless with several of his forgeries, and the panel of experts found traces of the modern pigment cobalt blue. In addition, they also detected the phenoformaldehyde (which was first discovered at the close of the 19th century) in several of the paintings. On the basis of this evidence Van Meegeren was convicted on October 12, 1947, and sentenced to one year in prison. While in prison he suffered a heart attack and died on December 30, 1947.

Despite the evidence gathered by the panel of experts, many people still refused to believe that the famed *Disciples at Emmaus* was forged by Van Meegeren. Their contention was based on the fact that the other alleged forgeries and Van Meegeren's nearly completed *Jesus Amongst the Doctors* were of a very inferior quality. Surely, they said, the creator of the beautiful *Disciples at Emmaus* could not produce such inferior pictures. Indeed, the *Disciples at Emmaus* was certified as an authentic Vermeer by the noted art historian A. Bredius and was bought by the Rembrandt Society for $170,000. The answer of the panel to these skeptics was that because Van Meegeren was keenly disappointed by his lack of status in the art world, he worked on the *Disciples at Emmaus* with the fierce determination of proving that he was better than a third-rate painter. After producing such a masterpiece his determination was gone. Moreover, after seeing how easy it was to dispose of the *Disciples at Emmaus* he devoted less effort to his subsequent forgeries. This explanation failed to satisfy the skeptics. They demanded a thoroughly scientific and conclusive proof that the *Disciples at Emmaus* was indeed a forgery. This was done in 1967 by scientists at Carnegie-Mellon University, and we would now like to describe their work.

The key to the dating of paintings and other materials such as rocks and fossils lies in the phenomenon of radioactivity discovered at the turn of the century. The physicist Rutherford and his colleagues showed that the atoms of certain "radioactive" elements are unstable and that within a given time period a fixed proportion of the atoms spontaneously disintegrates to form atoms of a new element. Because radioactivity is a property of the atom, Rutherford showed that the radioactivity of a substance is directly proportional to the number of atoms of the substance present. Thus, if $N(t)$ denotes the number of atoms present at time t, then dN/dt, the number of atoms that disintegrate per unit time, is proportional to N; that is,

$$\frac{dN}{dt} = -\lambda N. \tag{1}$$

The constant λ, which is positive, is known as the decay constant of the substance. The larger λ is, of course, the faster the substance decays. One measure of the rate of disintegration of a substance is its *half-life* which is defined as the time required for half of a given quantity of radioactive atoms to decay. To compute the half-life of a substance in terms of λ, assume that at time t_0, $N(t_0) = N_0$. Then the solution of the initial value problem

$$dN/dt = -\lambda N,\ N(t_0) = N_0$$

is

$$N(t) = N_0\, e^{-\lambda \int_{t_0}^{t} ds} = N_0\, e^{-\lambda(t-t_0)}$$

or $N/N_0 = e^{-\lambda(t-t_0)}$. Taking logarithms of both sides we obtain that

$$-\lambda(t - t_0) = \ln \frac{N}{N_0}. \tag{2}$$

Now, if $N/N_0 = 1/2$, then $-\lambda(t - t_0) = \ln 1/2$, so that

$$(t - t_0) = \frac{\ln 2}{\lambda} = \frac{0.6931}{\lambda}. \tag{3}$$

Thus the half-life of a substance is ln 2 divided by the decay constant λ. The dimension of λ, which we suppress for simplicity of writing, is reciprocal time. If t is measured in years, then λ has the dimension of reciprocal years, and if t is measured in minutes, then λ has the dimension of reciprocal minutes. The half-lives of many substances have been determined and recorded. For example, the half-life of carbon-14 is 5568 years, and the half-life of uranium-238 is 4.5 billion years.

Now the basis of "radioactive dating" is essentially the following. From (2) we can solve for $t - t_0 = (1/\lambda) \ln N_0/N$. If t_0 is the time the substance was initially formed or manufactured, then the age of the substance is $(1/\lambda) \ln N_0/N$. The decay constant λ is known or can be computed in most instances. Moreover, we can usually evaluate N quite easily. Thus, if we knew N_0, we could determine the age of the substance, but this is the real difficulty, since we usually do not know N_0. In some instances though, we can either determine N_0 indirectly, or else determine certain suitable ranges for N_0, and such is the case for the forgeries of Van Meegeren.

We begin with the following well-known facts of elementary chemistry. Almost all rocks in the earth's crust contain a small quantity of uranium. The uranium in the rock decays to another radioactive element, and that one decays to another, and another, and so forth, in a series of elements that results in lead (see Figure 4.1), which is not radioactive. The uranium (whose

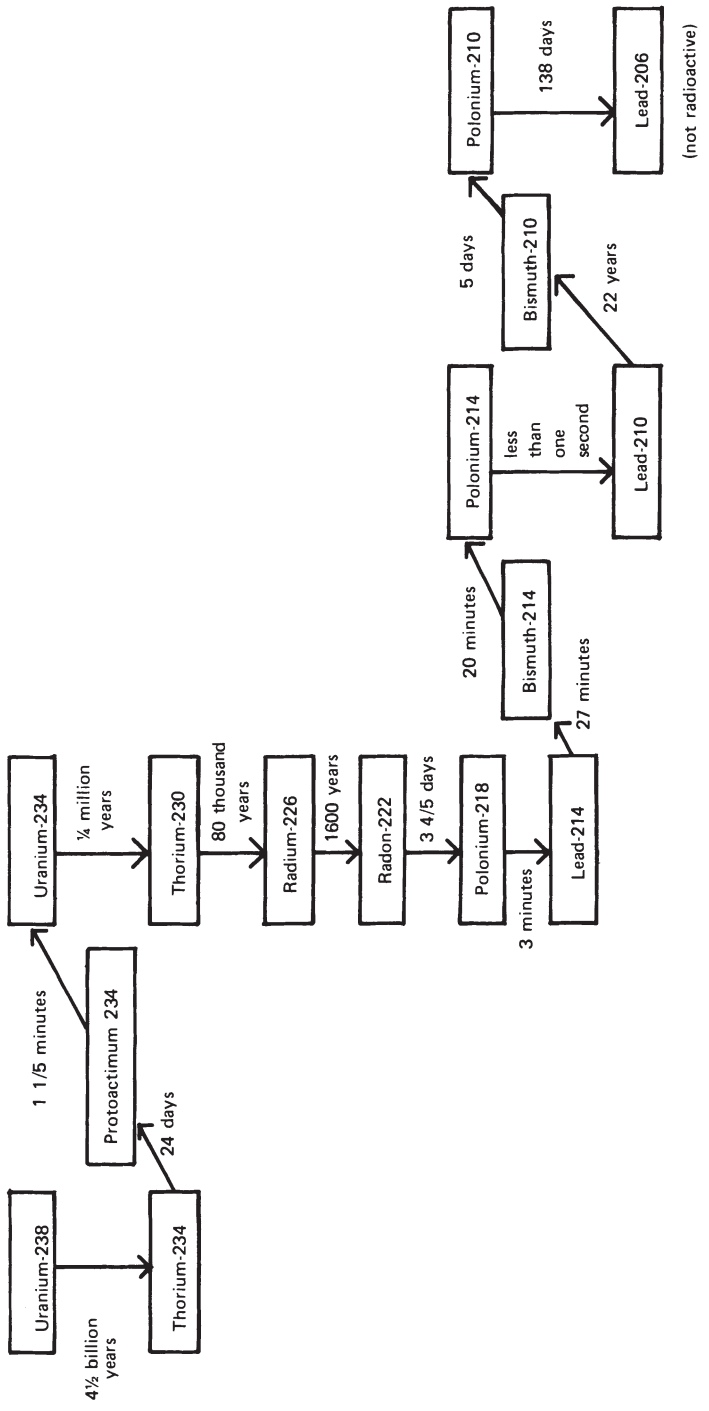

Figure 4.1. Uranium Series (Times shown on arrows are half-lives of each step.)

half-life is over 4 billion years) keeps feeding the elements following it in the series, so that as fast as they decay, they are replaced by the elements before them.

Now, all paintings contain a small amount of the radioactive element lead-210 (Pb^{210}) and an even smaller amount of radium-226 (Ra^{226}). These elements both occur in white lead (lead oxide), which is a pigment that artists have used for over 2000 years. For the analysis which follows, it is important to note that white lead is made from lead metal which, in turn, is extracted from a rock called lead ore in a process called smelting. In this process, the lead-210 in the ore goes along with the lead metal. However, 90–95% of the radium and its descendants are removed with other waste products in a material called slag. Thus most of the "supply" of lead-210 is cut off, and it begins to decay very rapidly, with a half-life of 22 yr. This process continues until the lead-210 in the white lead is once more in radioactive equilibrium with the small amount of radium present, i.e., the disintegration of lead-210 is exactly balanced by the disintegration of radium.

Let us now use this information to compute the amount of lead-210 present in a sample in terms of the amount originally present at the time of manufacture. Let $y(t)$ be the amount of lead-210 per gram of white lead at time t, y_0 the amount of lead-210 per gram of white lead present at the time of manufacture t_0, and $r(t)$ the number of disintegrations of radium-226 per-minute per gram of white lead at time t. If λ is the decay constant for lead-210, then

$$\frac{dy}{dt} = -\lambda y + r(t) \qquad y(t_0) = y_0. \tag{4}$$

Since we are only interested in a time period of at most 300 yr, we may assume that the radium-226, whose half-life is 1600 yr, remains constant, so that $r(t)$ is a constant r. Multiplying both sides of the differential equation by the integrating factor $\mu(t) = e^{\lambda t}$, we obtain $d(e^{\lambda t}y)/dt = r\,e^{\lambda t}$. Hence

$$e^{\lambda t}y(t) - e^{\lambda t_0}y_0 = (r/\lambda)(e^{\lambda t} - e^{\lambda t_0}),$$

or

$$y(t) = \frac{r}{\lambda}\left[1 - e^{-\lambda(t-t_0)}\right] + y_0\,e^{-\lambda(t-t_0)}. \tag{5}$$

Now $y(t)$ and r can be easily measured. Thus, if we knew y_0 we could use (5) to compute $(t - t_0)$, and consequently, we could determine the age of the painting. As we pointed out, though, we cannot measure y_0 directly. One possible way out of this difficulty is to use the fact that the original quantity of lead-210 was in radioactive equilibrium with the larger amount of radium-226 in the ore from which the metal was extracted. Let us, therefore, take samples of different ores and compute the rate of disintegration of radium-226. This was done for a variety of ores and the results are given in Table 1. These

Table 1. Ore and Ore Concentrate Samples

Description and Source	Disintegrations/min of Ra^{226}
Ore concentrate (Oklahoma–Kansas)	4.5
Crushed raw ore (S. E. Missouri)	2.4
Ore concentrate (S. E. Missouri)	0.7
Ore concentrate (Idaho)	2.2
Ore concentrate (Idaho)	0.18
Ore concentrate (Washington)	140
Ore concentrate (British Columbia)	1.9
Ore concentrate (British Columbia)	0.4
Ore concentrate (Bolivia)	1.6
Ore concentrate (Australia)	1.1

All disintegration rates are per minute per gram of white lead.

numbers vary from 0.18 to 140. Consequently, the number of disintegrations of the lead-210 per minute per gram of white lead at the time of manufacture will vary from 0.18 to 140. This implies that y_0 will also vary over a large interval, since the number of disintegrations of lead-210 is proportional to the amount present. Thus we cannot use (5) to obtain an accurate—or even a crude—estimate of the age of a painting. However, we can still use (5) to distinguish between a 17th-century painting and a modern forgery. The basis for this statement is the simple observation that if the painting is very old compared to the 22-year half-life of lead, then the amount of radioactivity from the lead-210 in a sample of paint will be nearly equal to the amount of radioactivity from the radium in the sample. On the other hand, if the painting is modern (20 years old or so) then the amount of radioactivity from the lead-210 will be much greater than the amount of radioactivity from the radium.

We can make this argument precise in the following manner. Let us assume that the painting in question is either very new or about 300 years old. Set $t - t_0 = 300$ in (5). Then after some simple algebra, we see that

$$\lambda y_0 = \lambda y(t)\, e^{300\lambda} - r(e^{300\lambda} - 1). \tag{6}$$

If our painting is indeed a modern forgery, then λy_0 should be absurdly large. To determine what is an absurdly high disintegration rate we observe (see Exercise 1) that if the lead-210 in a sample of white lead decays originally (at the time of manufacture) at the rate of 100 disintegrations (dis)/min per gram of white lead, then the ore from which it was extracted had a uranium content of 0.014%. This is a fairly high concentration of uranium since the average amount of uranium in rocks of the earth's crust is about 2.7 parts per million (ppm). On the other hand, some very rare ores exist in the western hemisphere whose uranium content is 2–3%. To be on the safe side, we will say that a disintegration rate of lead-210 is certainly absurd if it exceeds 30,000 dis/min per gram of white lead.

Table 2. Paintings of Questioned Authorship

Description	Po^{210} Disintegration	Ra^{226} Disintegration
Disciples at Emmaus	8.5	0.8
Washing of Feet	12.6	0.26
Woman Reading Music	10.3	0.3
Woman Playing Mandolin	8.2	0.17
Lace Maker	1.5	1.4
Laughing Girl	5.2	6

All disintegration rates are per minute per gram of white lead.

To evaluate λy_0, which is the number of disintegrations of the lead-210 per minute per gram of white lead at the time of manufacture, we must evaluate the present disintegration rate $\lambda y(t)$ of the lead-210, the disintegration rate r of the radium-226, and $e^{300\lambda}$. Since the disintegration rate of polonium-210 (Po^{210}) equals that of lead-210 after several years, and since it is easier to measure the disintegration rate of polonium-210, we substitute these values for those of lead-210. To compute $e^{300\lambda}$, observe from (3) that $\lambda = \ln 2/22$. Hence

$$e^{300\lambda} = e^{(300/22)\ln 2} = 2^{150/11}.$$

The disintegration rates of polonium-210 and radium-226 were measured for the *Disciples at Emmaus* and various other alleged forgeries and are given in Table 2.

If we now evaluate λy_0 from (6) for the white lead in the painting *Disciples at Emmaus*, we obtain that

$$\begin{aligned}\lambda y_0 &= 2^{150/11}(8.5) + 0.8(2^{150/11} - 1) \text{ dis/min/g of Pb} \\ &= 98{,}050\end{aligned}$$

which is unacceptably large. Hence this painting must be a modern forgery. By a similar analysis (see Exercises 2–4) the paintings *Washing of Feet*, *Woman Reading Music*, and *Woman Playing Mandolin* were indisputably shown to be faked Vermeers. On the other hand, the paintings *Lace Maker* and *Laughing Girl* cannot be recently forged Vermeers, as claimed by some experts, since for these two paintings, the polonium-210 is very nearly in radioactive equilibrium with the radium-226, and no such equilibrium has been observed in any samples from 19th- or 20th-century paintings.

Exercises

1. In this exercise we show how to compute the concentration of uranium in an ore from the disintegration of the lead-210 in the ore.
   a) The half-life of uranium-238 is 4.51×10^9 yr. Since this half-life is so large,

we may assume that the amount of uranium in the ore is constant over a period of 200–300 yr. Let $N(t)$ denote the number of atoms of U^{238}/g of ordinary lead in the ore at time t. Since the lead-210 is in radioactive equilibrium with the uranium-238 in the ore, we know that $dN/dt = -\lambda N = -100$ dis/min/g of Pb at time t_0. Show that there are 3.42×10^{17} atoms of uranium-238/g of ordinary lead in the ore at time t_0. *Hint:* 1 yr = 525,600 min.

b) Using the fact that one mole of uranium-238 weighs 238 g and that a mole contains 6.02×10^{23} atoms, show that the concentration of uranium in the ore is approximately 0.014%.

For the paintings in Exercises 2, 3, and 4 use the data in Table 2 to compute the disintegrations per minute of the original amount of white lead per gram of ordinary lead, and conclude that each of these paintings is a forged Vermeer.

2. *Washing of Feet.*

3. *Woman Reading Music.*

4. *Woman Playing Mandolin.*

5. The following problem describes a very accurate derivation of the age of uranium.
   a) Let $N_{238}(t)$ and $N_{235}(t)$ denote the number of atoms of U^{238} and U^{235} at time t in a given sample of uranium, and let $t = 0$ be the time this sample was created. By the radioactive decay law,

$$\frac{d}{dt}N_{238}(t) = \frac{-\ln 2}{(4.5)10^9}N_{238}(t)$$

$$\frac{d}{dt}N_{235}(t) = \frac{-\ln 2}{0.707(10)^9}N_{235}(t).$$

   Solve these equations for $N_{238}(t)$ and $N_{235}(t)$ in terms of their original numbers $N_{238}(0)$ and $N_{235}(0)$.

   b) In 1946 the ratio of U^{238}/U^{235} in any sample was 137.8. Assuming that equal amounts of U^{238} and U^{235} appeared in any sample at the time of its creation, show that the age of uranium is 5.96×10^9 yr. This figure is universally accepted as the age of uranium.

6. In a samarskite sample discovered recently, there was 3 g of Thorium (Th^{232}). Thorium decays to lead-208 (Pb^{208}) through the reaction $Th^{232} \rightarrow Pb^{208} + 6(4He^4)$. It was determined that 0.0376 g of lead-208 was produced by the disintegration of the original Thorium in the sample. Given that the half-life of Thorium is 13.9 billion years, derive the age of this samarskite sample. (Hint: 0.0376 g of Pb^{208} is the product of the decay of $232/208 \times 0.0376$ g of Thorium.

One of the most accurate ways of dating archaeological finds is the method of carbon-14 (C^{14}) dating discovered by Willard Libby around 1949. The basis of this method is delightfully simple. The atmosphere of the earth is continuously bombarded by cosmic rays. These cosmic rays produce neutrons in the earth's atmosphere, and these neutrons combine with nitrogen to produce C^{14}, which is usually called radiocarbon since it decays radioactively. This radiocarbon is incorporated in carbon dioxide and thus moves through the atmosphere to be absorbed by plants. Animals, in turn, build radiocarbons into their tissues by eating the plants. In living

tissue, the rate of ingestion of C^{14} exactly balances the rate of disintegration of C^{14}. When an organism dies, though, it ceases to ingest carbon-14, and thus its C^{14} concentration begins to decrease through disintegration of the C^{14} present. Now, it is a fundamental assumption of physics that the rate of bombardment of the earth's atmosphere by cosmic rays has always been constant. This implies that the original rate of disintegration of the C^{14} in a sample such as charcoal is the same as the rate measured today.[1] This assumption enables us to determine the age of a sample of charcoal. Let $N(t)$ denote the amount of carbon-14 present in a sample at time t, and N_0 the amount present at time $t = 0$ when the sample was formed. If λ denotes the decay constant of C^{14} (the half-life of carbon-14 is 5568 yr) then $dN/(t)/dt = -\lambda N(t)$, $N(0) = N_0$. Consequently, $N(t) = N_0 e^{-\lambda t}$. Now the present rate $R(t)$ of disintegration of the C^{14} in the sample is given by $R(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$ and the original rate of disintegration is $R(0) = \lambda N_0$. Thus $R(t)/R(0) = e^{-\lambda t}$ so that $t = (1/\lambda)\ln(R(0)/R(t))$. Hence if we measure $R(t)$, the present rate of disintegration of the C^{14} in the charcoal and observe that $R(0)$ must equal the rate of disintegration of the C^{14} in a comparable amount of living wood, then we can compute the age t of the charcoal. The following two problems are real-life illustrations of this method.

7. Charcoal from the occupation level of the famous Lascaux Cave in France gave an average count in 1950 of 0.97 dis/min/g. Living wood gave 6.68 disintegrations. Estimate the date of occupation and hence the probable date of the remarkable paintings in the Lascaux Cave.

8. In the 1950 excavation at Nippur, a city of Babylonia, charcoal from a roof beam gave a count of 4.09 dis/min/g. Living wood gave 6.68 disintegrations. Assuming that this charcoal was formed during the time of Hammurabi's reign, find an estimate for the likely time of Hammurabi's succession.

References

[1] P. Coremans, *Van Meegeren's Faked Vermeers and De Hooghs.* Amsterdam: Meulenhoff, 1949.

[2] B. Keisch, R. L. Feller, A. S. Levine, and P. R. Edwards, "Dating and authenticating works of art by measurement of natural alpha emitters, *Science*, *155*, 1967, pp. 1238–1241.

[3] ——, "Dating works of art through their natural radioactivity: Improvements and applications," *Science*, *160*, 1968, pp. 413–415.

[4] ——, *The Mysterious Box: Nuclear Science and Art*, a *World of the Atom* series booklet.

[1] Since the mid-1950's, the testing of nuclear weapons has significantly increased the amount of radioactive carbon in our atmosphere. Ironically, this unfortunate state of affairs provides us with yet another powerful method of detecting art forgeries. To wit, many artists' materials, such as linseed oil, canvas, paper, and so on, come from plants and animals, and so will contain the same concentration of carbon-14 as the atmosphere at the time the plant or animal dies. Therefore, linseed oil (which is derived from the flax plant), for example, that was produced during the last few years will have a much greater concentration of carbon-14 in it than linseed oil produced before 1950.

Notes for the Instructor

Objectives. The module shows how the radioactive decay of certain substances in white lead was used to prove that the famed painting *Disciples at Emmaus* bought by the Rembrandt Society for $170,000 was a forged Vermeer.

Prerequisites. First-order linear nonhomogeneous differential equations.

Time. The module can be covered in one or two lectures.