

**Thomas Harriot on the Coins of England**

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Thomas Harriot was the finest English mathematician before Isaac Newton, but his work on the coinage of his country is almost unknown, unlike Newton’s. In the early 1600s Harriot carried out complicated calculations relating to the gold and silver coins of his time. He analysed the true ratio between gold and silver, using data derived from the weights and values of the coins. He also did experimental work on the coins, using hydrostatic weighing.

None of Harriot’s work was published in his lifetime, but a very large number of his manuscripts are now available for study online. This talk is intended to draw attention to the historical significance of this material, from several points of view. There are insights into the troubles that beset Sir Walter Ralegh and the earl of Northumberland, both of whom were patrons of Harriot. Economic historians will find some interesting details of the monetary history of the early Stuart period. And historians of mathematics will find evidence of the rapid advances that were taking place at that time, both in arithmetic and symbolic algebra, topics in which Harriot was at the forefront.

**Making Gold and Silver Coins**

By the time of the Roman occupation of Britain, the notion had emerged that a *coin* was a lump of metal with a value guaranteed by the authority of the maker. When coins were made of precious metal, such as the silver in the Roman denarius, their value was originally determined by their weight and fineness. However, the Romans found that the stamp of authority could be used without the underlying integrity, and so their denarii gradually became debased, to the point where their silver content was minimal.

By the 13th century there were many kinds of ‘silver’ coins in circulation. In England it had been decided that the king’s coins should conform to the *sterling* standard, over 90% pure silver. But much of the ‘silver’ that was available for use at the king’s mints was of worse fineness, and so it had to be mixed with silver of better fineness in order to make the coins.

The arithmetical rules for making mixtures of this kind were described in Fibonacci’s *Liber Abbaci*, written in the early 1200s, and by the end of the century the rules were in use at the London mint. The subject became known as *alligation*, and when printed books on Arithmetic became available, this was one of the standard topics. There were many variations of the basic principle but, as was the custom at that time, the calculations were justified only by informal arguments. It was not until around 1600 that Thomas Harriot used his new algebraic notation to provide a formal *proof.*

**The Gold-Silver Ratio**

Another topic studied by Harriot was the *ratio*. A proclamation of 16 November 1604 declared that the values for the new coins of King James would be based on two rules:

* one troy pound of crown gold = 744 shillings.
* one troy pound of sterling silver = 62 shillings.

The weights of individual coins were also given in the proclamation, calculated according to the ‘weight-value’ principle that the values of coins of a specific metal must be directly proportional to their weights. For example, a sterling silver coin with value one shilling should weigh 1/62 of a troy pound.

The most noteworthy aspect of the proclamation was that the ratio of the values for crown gold and sterling silver was 744/62, which is exactly 12. This neat arrangement was clearly convenient, but it did not tell the whole story. The coinage metals, crown gold and sterling silver, were not the same as pure gold and pure silver respectively, but only partly so. In fact, it was specified that crown goldshould contain 11 parts in 12 of pure gold, andsterling silver should contain 37 parts in 40 of pure silver, by weight. In the international markets the ratio of the pure metalswas important because it determined whether profits could be made by arbitrage: that is, by exchanging British coins with those of another country where the ratio was different.

Given that the declared ratio for the coined metals is 12, one method of calculating the implied ratio for the pure metals is as follows. Since crown goldcontains 11 parts of goldin 12, and sterling silver contains 37 parts of silver in 40, the figures for the pure metals are:

* one troy pound of pure gold = (12/11) x 744 shillings*.*
* one troy pound of pure silver= (40/37) x 62 shillings.

This gives the ratio:

The fact that the fineness of crown gold (11/12 = .916) is close to the fineness of sterling silver (37/40 = .925) has ensured that the ‘true’ ratio is close to the declared one. However, in the international bullion markets, the difference could be significant.

**Harriot and His Patrons**

For most of his life Thomas Harriot was supported by two famous patrons, Sir Walter Ralegh and Henry Percy, ninth earl of Northumberland. In these fortunate circumstances he was able to devote almost all his time and energy to his scientific work, without the need to obtain financial support by publishing his results. But the patronage also had negative aspects: he would be affected when the slings and arrows of outrageous fortune were directed against his patrons, as indeed they were.

In the 1580s Harriot had accompanied Ralegh on a voyage to North America, during which he used his mathematical abilities to improve methods of navigation. His association with Ralegh continued into the 1590s, when he also became one of the scholars supported by the earl of Northumberland. Over 8000 pages of his manuscript notes have survived, and much of this work was far ahead of its time. Only since 2011 has it become possible to make a comprehensive study of the papers, thanks to the publication of the entire archive under the auspices of the European Cultural History Online.

Ralegh’s relationship with Queen Elizabeth had often been stormy, and the queen’s death in March 1603 was soon followed by a charge of high treason against him. After a strange trial, during which the leading lawyers of the day presented unsubstantiated allegations as if they were established facts, Ralegh was found guilty and condemned to death. The sentence was suspended by King James, but Ralegh was confined in the Tower of London at the king’s pleasure. Harriot had helped with the preparation of Ralegh’s defence, and this led to vitriolic denunciation of him by the prosecutors, on the grounds (among others) that he had encouraged Ralegh in atheistic beliefs. This verbal assault, by some of the most powerful men in the land, seems to have had a devasting effect, because there is no evidence in Harriot’s papers of any scientific work for about eight months after 18 September 1603.

**Harriot’s Calculations of the Ratio**

Harriot’s work on the gold-silver ratio is undated, but the context suggests that it was done in the early years of the 17th century. His main concern was *angel gold*, a metal used in England for coins of gold since the thirteenth century. It contained only 1 part in 192 of alloy, in contrast to the *crown gold* discussed in Section 2, which was introduced in 1523, and contained 1 part in 12 of alloy. The name angel gold arose because the most common coin struck from this metal was the angel, traditionally valued at 10 shillings and struck at the rate of 72 to the troy pound of 5760 grains, so that each angel weighed exactly 80 grains. These figures had been used throughout most of Elizabeth’s reign.

Harriot first considered the angels weighing 80 grains, assuming the traditional value of 10 shillings. This corresponds to a coined metal with the property that 60 shillings-worth of it weighs 480 grains. According to the proclamation of 1604, 60 shillings-worth of the current sterling silver weighed (60/62) x 5760 = 5574.193 grains, so the ratio for angel gold to sterling silver was:

(5574.193)/480 = 11.6129.

Harriot next obtained the ratio for the pure metals ‘if both the alloys be reckoned as of no value’, which gives the result 10.7981. Finally, he did the calculation ‘if the value of the [silver] in the gold be reckoned for’, which leads to the ratio10.7929. Finally, he repeated the calculations, assuming that the angels were to be valued 11 shillings or 12 shillings.

The fact that there are three calculations, based on three different assumptions about the value of an angel coin, suggests some possible scenarios for this work. The intention may have been to estimate the true value of some old Elizabethan angels, both nationally (based on the current sterling silver coins) and internationally (based on the implied ratio of gold to silver). Another motivation could have stemmed from Northumberland’s position in the government. Henry Percy been assiduous in cultivating the favour of James Stuart and, shortly after the latter was proclaimed king of England in 1603, he had been admitted to the Privy Council. James had already been king of Scotland for many years, and the systems of coinage in the two countries were quite different. With aid of the Council, James set out to reconcile them, and surely Henry Percy would have been involved in discussions about the new coinage.

**Harriot’s Experiments on the Density of Gold and Silver Coins**

After the trauma of Ralegh’s trial, the first sign of Harriot resuming his scientific work is found in three folios, all dated 25 July 1604. There he lists the results of some experiments on the density of salt solutions. In the following months of 1604, he carried out a series of similar experiments on many other substances, including gold and silver coins.

The main motivation for Harriot’s work on density came from two of his long-standing lines of research. One was the refraction of light, where in the 1590s he had already discovered the rule now known as Snell’s Law, after the man who rediscovered it a few decades later. The second line of research was ballistics, where he had conducted many experiments on the rate at which objects fall. However, his study of gold and silver coins could not have been directly inspired by questions of optics or ballistics, and clearly it had more mundane origins.

The density of a substance is defined as the mass of a unit volume. Nowadays the unit of mass is the gram, and the unit of volume is the cubic centimetre. These units were defined in the 1790s, so that the mass of a cubic centimetre of water is one gram, and the density of water is 1. Very few precise measurements of density had been carried out before Harriot began his experiments, and most of them had been done by the direct method, which involves preparing a known volume of the substance and then weighing it. Both these operations required great skill and precision, and the results were unreliable. The main feature of Harriot’s experiments was the use of hydrostatic weighing, which had its origins in Archimedes’ famous Eureka moment: the realisation that when an object is immersed in water it experiences a buoyancy, which can be equated to the weight of the water it displaces. This principle is not only a deep theoretical insight, it also provides a method of measuring the density of an object. If the weight in air is W1, and the weight in water is W2, the buoyancy W1 - W2 is the weight of a quantity of water equal in volume to the object. The ratio of W1 to W1 - W2 is thus a measure of the density of the object in comparison to water, often called its *relative density* or *specific gravity*.

In the autumn of 1604 Harriot used the hydrostatic method in a series of experiments on the density of gold and silver coins. The table below is a transcript of an experiment in which the relative density of angel gold (☉) with respect to water was found to be 17829:1000.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| In aere ☉ | | 2 ½ ¼ ⅛ 0 [oz]. 1 [dwt] 4½ gr | | 1408½ |
| In aqua ☉ | | 2 ½ ¼ 0 0 . 9½ gr | | 1329½ |
| [?]motus aequalis  aqua | | ⅛ 0 . 19 gr | | 79 |
|  | |  | |  |
| Ratio | |  | |  |
| aqua | ☉ | |  |  |
| 79 | 1408½ | |  |  |
| 1000 | 17829 | |  |  |

The coins were first weighed in air (W1 = 1408½ grains) and then in water (W2 = 1329½ grains), using a set of weights denominated in ounces, pennyweights, and grains. (1 ounce = 20 pennyweights = 480 grains.) Since the difference W1 – W2 was 79 grains, the ratio of angel gold to water was 1048½:79, or 17829:1000.

Another of Harriot’s experiments was designed to check the composition of the angel gold coins. Here are the results.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | ☉ ♀  191 1 | ☉ fine  19151 |
| Angel gold in aere | 9229.9 | 9181.9 48.0  9229.9 |  |
| Angel gold in aqua | 8745.1 |  |  |
| aqua | 484.8 | 479.4 5.4  484.8 | 1000 |

On the left are the weights, in air, in water, and the difference, of a set of 118 angel coins. In the next column, headed ☉, there is the implied weight of the 191 parts of pure gold, 9181.9 grains, and the weight of the corresponding volume of water, 479.4 grains, calculated by taking the relative density of pure gold to be 19151:1000 (NOT the figure in f.113r). In the next column the figures for the 1 part of alloy are calculated by subtraction, thus: 9229.9 – 9181.9 = 48.0, 484.8 – 479.4 = 5.4. The implication of these figures is that the relative density of the alloy is 48.0:5.4, that is, 8889:1000. The conclusion is revealed by the symbol he placed at the head of the ‘alloy’ column. It is not ☽ (silver),it is♀ (copper). He had found that the ‘alloy’ in angel gold was not pure silver (density = 10529), but mainly copper (density 8795).

**Harriot and His Legacy**

In the autumn of 1605, the problems of James and his government once again impinged on Harriot and his patrons. A small group of disaffected persons conceived the idea that England would be a better place if the king and all his ministers were murdered. The plan was foiled at the last moment, with the arrest of Guy Fawkes in the early hours of Tuesday, 5 November 1605, and it quickly emerged that one of the plotters was Thomas Percy, a distant relation of Henry Percy. The earl was interrogated at length, but no evidence of his involvement in the gunpowder plot was ever found. Nevertheless, he was confined in the Tower of London, where he remained for the next 16 years. Harriot was also imprisoned in the Tower, but only temporarily.

Harriot was unwell during his imprisonment, but he was eventually released and was able to resume his scientific work. His interests turned towards astronomy, where his expertise in optics was put to good use. One of his most significant achievements was to construct a telescope and use it to draw features that he observed on the surface of the moon. This was in July 1609, four months before Galileo’s more famous observations.

Although Harriot’s earlier work on hydrostatic weighing and the coinage remained obscure, it was not completely forgotten. Indeed, now that we have a better understanding of the details, it is possible to argue that, in the decades after his death in 1621, it became significant in the affairs of the nation. The central character was Thomas Aylesbury. The earliest known record of his friendship with Harriot is a letter dated 15 April 1611, in which he thanks Harriot for sending some spectacles for the earl of Nottingham, the Lord High Admiral, who was at that time Aylesbury’s superior in the king’s service. The letter is written is a friendly style, which suggests that Harriot and Aylesbury were already acquainted.

Shortly before his death in 1621 Harriot wrote a will, under the terms of which Aylesbury, together with Nathaniel Torporley, John Protheroe, and Walter Warner, were all to be involved in the fate of his papers. Torporley was to be the ‘Ouerseer of my Mathematicall writings’. He was charged with preparing them for publication, with the assistance of Warner and others if necessary, and under the supervision of Aylesbury and Protheroe, who were two of the executors. The papers contained the draft of a *Treatise on Equations*, and it was natural for Torporley to regard the preparation of this material as his first task. But progress towards publication was slow, and eventually Aylesbury lost patience. He discharged Torporley and entrusted the work to Walter Warne, who was a well-respected scholar with wide scientific interests. By 1631 Warner had prepared a selection of the papers for publication, and a book was published under the title *Artis Analyticae Praxis*.

By the time the *Praxis* appeared in print, Aylesbury had become a power in the land. He had been installed as a Master of Requests in 1627, raised to the peerage as a baronet, and his upward trajectory was to continue when he was given control of the nation’s coinage. In 1631 he was appointed as the sole ‘maker of weights and balances for the king’s moneys of gold’, and in 1635 he became joint master of the Tower Mint in London. Until now his qualifications for these appointments have been open to question, but his familiarity with Harriot’s papers, which contained research on the gold and silver coins, may well be the key. This material would have been highly relevant to his work at the Mint. Indeed, Warner produced a tract on the ‘Commixture of Metals’. almost certainly at Aylesbury’s request, and since Harriot’s work would have been available to Warner, it may well have been the basis of his tract.

In 1642 the rift between Parliament and King Charles escalated into civil war. The Tower Mint was taken over by parliamentary forces in August 1642, and Aylesbury moved to the royalist stronghold at Oxford, where he continued to serve as Master of Requests. Walter Warner died soon afterwards, and work on the Harriot papers must have ceased. Aylesbury died in Breda in 1657 and the whereabouts of Harriot’s papers remained a mystery for many years, in spite of several attempts to locate them. Harriot’s will had decreed that, after work on the papers had finished, the executors should put them ‘in a Convenient Trunk with a lock and key […] to be placed in my Lord of Northumberlands Library‘. In 1784 a large collection of Harriot’s papers was indeed found at Petworth House in Sussex, the stately home of the Percy family. So, it seems that Aylesbury had correctly played his part in the execution of the will, although how this happened, when this happened, and whether all the papers were present, remains unclear.

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**Notes and References**

* Harriot’s manuscripts can be viewed online[**here**](https://echo.mpiwg-berlin.mpg.de/content/scientific_revolution/harriot).
* For a full account of Harriot’s life, see John Shirley, *Thomas Harriot: A Biography* (Oxford: Clarendon Press, 1983).
* This talk is based on my article ‘Thomas Harriot on the Coinage of England’ *Archive for the History of the Exact Sciences* 73 (2019) 361-383.
* For more details of the numismatic context see my articles: ‘Without Grains: Weighing Silver Coins in the Civil War’, *British Numismatic Journal* 88 (2018) 77-87; ‘John Reynolds of the Mint: A Mathematician in the Service of King and Commonwealth’, *Historia Mathematica* 48 (2019) 1-28.