Galileo as Gemmologist: The First Attempt in Europe at Scientifically Testing Gemstones

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Galileo Galilei is credited with being one of the greatest contributors to the 'scientific revolution', particularly because of his discoveries in astronomy. He also introduced into European gemmology his 'language of mathematics' (i.e. experimental science) with the invention of the *bilancetta* (little [hydrostatic] balance). He conceived it to recheck Archimedes' determination of the gold content of a royal crown, and also used this balance to measure the mass of 23 gem samples in air and in water. However, much of his data was inconsistent with the inferred identity of his samples, since many were simulants. The results of his investigations did not circulate, and only after three centuries was Galileo's handwritten *tavola* (table) of gem data discovered.

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Introduction

In 1586 Galileo Galilei (1564–1642; Figure 1), a 22-year-old drop-out from the University of Pisa, returned to Florence and wrote a short essay describing a hydrostatic method (Figure 2) for testing precious metal alloys. He developed the technique to improve upon the methodology articulated by Vitruvius (1567, IX.10–12), who described the ancient Greek scientist Archimedes' efforts to verify the composition of the gold in the crown of King Hiero (the Greek Sicilian king of Syracuse from 270 to 215 BC). Archimedes devised a method based on buoyancy, and determined that the crown was not pure gold but rather a silver-gold alloy. Galileo did not believe in the fairly simple solution reported by Vitruvius and looked for a more sophisticated one, also based on buoyancy, but with rigorous hydrostatic constraints. He wrote his essay in Italian, in a first attempt at breaking the use of Latin as the universal language of science and scholarly pursuits. Indeed, the name *bilancetta* (little [hydrostatic] balance) plays down, perhaps intentionally, the instrument he conceived and built; his balance was far from being little, with a yoke over 1 m long. Galileo tested his new instrument on three metals (gold, silver and copper) and, seeing that it worked well, pursued additional measurements on gem materials (see below).

Galileo's results exceeded his own expectations, going beyond Archimedes' ingenuity. Even so, he set aside his manuscript (and the balance) and forgot it. Only several years later, after he had attained wide notoriety in Europe because of his discoveries in astronomy, did he allow one of his pupils (Benedetto Castelli) to copy the essay. After

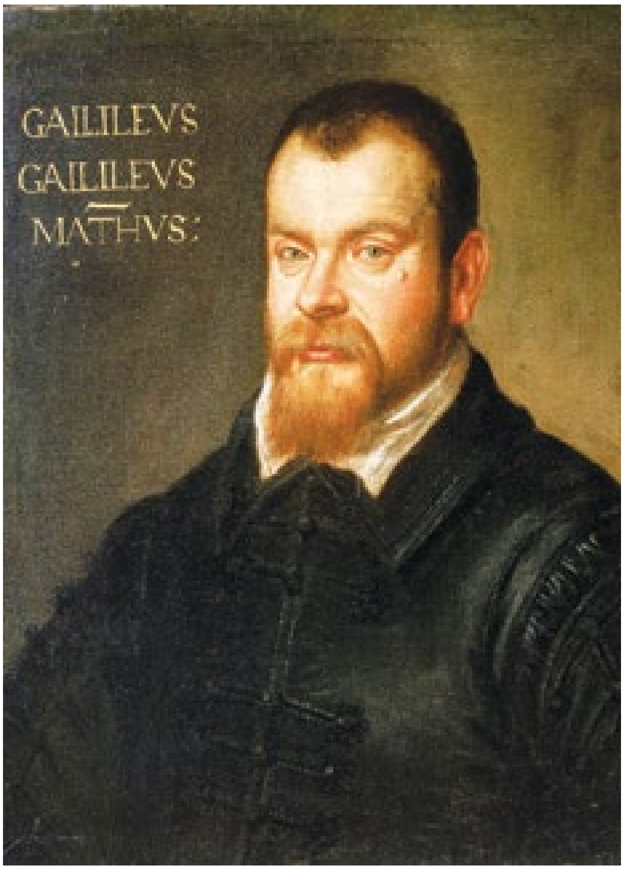

Figure 1: This portrait of Galileo as a professor of mathematics at Padua University was painted in 1605 by Domenico Tintoretto (Domenico Robusti; Venice, 1560–1635).

Galileo died, one of his followers from Palermo (Gian Battista Hodierna) dared to print it, being careful to forge a vague title to avoid stirring the suspicions of the Inquisition (Hodierna, 1644). *La Bilancetta* appeared under this title in all early editions of Galileo's *Opera* (Collected Works)—Bologna (1656), Florence (1717) and Padua (1744)—and in numerous others until the publication of the state-sponsored Edizione Nazionale (National Edition) compilation by Favaro (1890). It was not translated into a foreign language until Fermi and Bernardini (1961) published a selection of Galileo's works in English.

Archimedes' approach to verifying the composition of the gold in King Hiero's crown had stirred interest among many people, leaving them unsatisfied with the technique described by Vitruvius. The hydrostatic weighing solution suggested by Galileo generated a few imitations and improvements, as well as clever alternatives (e.g. the pycnometer made by Wilhelm Homberg in 1699 and the aerometer devised by William Nicholson in 1785). Nevertheless, that was all. Information from the Arab world—where effective instruments to hydrostatically measure gem materials had been used since the 10th century AD (e.g. by al-Rāzi, al-Bīrūnī and al-Khāzinī, just to mention a few)—had not arrived in Europe, or such knowledge was too vague to give rise to substantial practical results.

The reason for the scientific community's lack of consideration or recognition of *La Bilancetta* probably lies in an editorial blunder. When Castelli copied the essay, he omitted the three sheets containing the results originally described by his master: those that are now known as the *tavola* (table). So, when Hodierna asked Castelli for a copy of the essay, he received only the description of the instrument, but no examples of its application. The incomplete work was published by Hodierna, as well as by all subsequent compilers of Galileo's works, for almost three centuries. The *tavola* was finally discovered in 1879 by Antonio Favaro, a mathematician and science historian who was collecting everything written by Galileo and his pupils in an effort to compile an official complete edition of his work. Favaro found a few of Galileo's handwritten papers inserted in the surviving scripts preserved at the Florence National Library (Par. II. T. XVI. Car. 60–62), relating to *La Bilancetta* (Par. II. T. XVI. Car. 55). Favaro immediately published them under the title *Tavola delle proporzioni delle gravità in specie de' metalli e delle gioje pesate in aria ed in aqqua* (Table of the proportions of gravities

Figure 2: (Top) Galileo's original schematic diagram of his hydrostatic balance as it appears in his draft manuscript (Mss. Galil. Vol. 45, Car. 55v, Raccolta Palatina, Biblioteca Nazionale di Firenze) and (bottom) redrawn in the Edizione Nazionale of his collected works (Favaro, 1890, p. 217). Key: a–b = balance yoke; b = weight; c = suspension point; d = counterweight in air; e = counterpoise in water for pure gold; f = counterpoise in water for pure silver; g = counterpoise in water for a metal alloy or gem material.

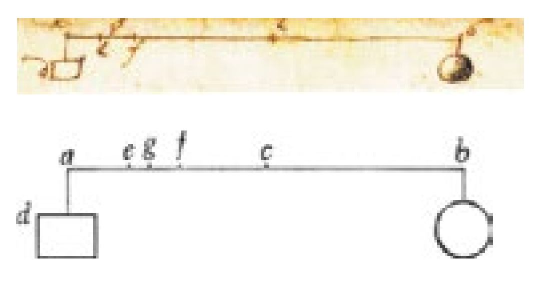

Figure 3: The first hand-written page of the 'Table of the proportions of gravities especially of metals and gems weighed in air and water' by Galileo (Mss. Galil. Vol. 45, Car.60r, Raccolta Palatina, Biblioteca Nazionale di Firenze). The weighing unit was the Florentine grain (1 grain = 0.5894 gram). It was followed by additional sheets containing the results obtained during two sessions of measurements.

especially of metals and gems weighed in air and water; Favaro, 1879). Indeed, this was a slightly modernized version of the title given by Galileo himself (Figure 3). Favaro later republished the table, with trifling modifications in the numbers, in Book 1 of Edizione Nazionale (Favaro, 1890, pp. 211–212) which contains all the works by the young Galileo: the *Juvenilia* (Youth Works; cf. Castagnetti and Camerota, 2001).

Surprisingly, the publication of Galileo's experimental data did not spur scientists to a thorough analysis of the results. The one exception was the German doctoral student Heinrich Bauerreiß: in his dissertation he calculated SG values from the experimental data recorded in the table, for metals and gem materials alike. He pointed out how good the data were for the metals, but did not comment on the gems (Bauerreiß, 1914, pp. 62–64).

The Materials Studied by Galileo

Why Galileo measured the buoyancy behaviour of metals is obvious: he wanted to find a better method than the one devised by Archimedes and described by Vitruvius. For pure metals, Galileo's measurements yield SGs of 19.53 for gold (versus a calculated ideal density value D = 19.302 g/cm^3), 10.46 for silver (D = 10.497 g/cm^3) and 8.83 for copper (D = 8.930 g/cm^3). His data were quite close to the ideal calculated values, although somewhat higher for the heaviest metal and lower for the lighter ones. Such results were obtained without many of the experimental constraints required by modern methods, thus showing that the young Galileo was possibly still rather crude as an experimental scientist, but his results were trustworthy. Indeed, the scatter is less than ~1%. In addition, Galileo tested metals used for minting coins: the gold-silver alloy of an *óngaro* (Hungarian ducat) and the silver-lead alloy of a *testone* (one fourth of a Florence gold ducat, locally called a *fiorino* or florin). His data showed that their SG values were lower than those of refined metals, but within the expectation of what was then considered an honest mintage composition (~2%): their calculated finenesses were 968‰ and 987‰, respectively.

Galileo tested an even greater number of gem materials (Table I). He apparently made the measurements in two sessions, as the table consists of two parts written on separate sheets. In the first session, the paper sheet (Par. II. T. XVI. Car. 60r–60v; e.g. Figure 3) lists: *diamante* (diamond), *rubini* (ruby), *smeraldo* (emerald), *topazio* (topaz) and *zaffiri* (sapphire). In the second one, the two paper sheets (Par. II. T. XVI. Car. 61r–62v) list again the data for the same gems and, in addition: *crisolito* (chrysolite, referring to peridot), *turchina* (turquoise), *perla* (pearl), *granata* (garnet), *calcidonio* (chalcedony), *amatista* (amethyst), *aqqua marina*

Table I: The gem materials studied by Galileo, with their inferred identification via calculated SG values.[a]

Name given by Galileo	Expected SG range[b]	Weight in air (grains)[c]	Weight in water (grains)[c]	Calculated SG[d]	Inferred identification	Range of known SGs[e]
Session 1						
Diamante	3.50–3.53	48.17	34.59	3.55	Colourless topaz	3.49–3.57
Rubini 3	4.00	16.56	12.44	4.02	Ruby	4.00
Smeraldo	2.67–2.78	133.22	84.16	2.72	Emerald	2.67–2.78
Topazio	3.49–3.57	381.25	242.50	2.75	Heliodor	2.68–2.74[f]
Zaffiri 2	4.00	10.50	7.56	3.57	Blue spinel	3.54–3.63
Session 2						
Diamante	3.50–3.53	48.17	34.59	3.55	Colourless topaz	3.49–3.57
Smeraldo	2.67–2.78	133.22	84.16	2.72	Emerald	2.67–2.78
Topazio	3.49–3.57	210.34	131.19	2.66	Citrine	2.65
Crisolito	3.28–3.38	310.19	217.88	3.36	Peridot	3.28–3.38
Crisolito	3.28–3.38	68.56	40.94	2.48	Green glass	Variable
Topazio	3.49–3.57	381.25	242.50	2.75	Heliodor	2.64
Zaffiro	4.00	5.75	4.25	3.83	Gahnospinel(?)	3.54–4.00
Rubini 3	4.00	16.56	12.44	4.02	Ruby	4.00
Rubino	4.00	49.10	35.31	3.56	Red spinel	3.54–3.63
Zaffiri 2	4.00	10.50	7.56	3.57	Blue spinel	3.54–3.63
Turchina	2.31–2.84	36.75	23.31	2.73	Turquoise	2.31–2.84
Turchina	2.31–2.84	22.81	14.56	2.77	Turquoise	2.31–2.84
Perla	2.60–2.85	91.88	56.38	2.59	Pinctada sp. pearl or nacre	2.60–2.85
Perla	2.60–2.85	29.13	19.00	2.88	Strombus sp. (conch) pearl	2.18–2.87
Granata	3.78–4.10	89.77	64.88	3.61	Grossular (hessonite)	3.57–3.65
Granata	3.78–4.10	224.50	168.13	3.98	Pyrope-almandine	3.80–3.95
Zaffiro	4.00	103.38	63.25	2.58	Blue glass (or iolite?)	Variable (or 2.58–2.66)
Calcidonio	2.58–2.64	61.56	37.94	2.61	Chalcedony	2.58–2.64
Smeraldo	2.67–2.78	192.25	129.63	3.07	Tourmaline (uvite)	2.82–3.32
Crisolito	3.28–3.38	102.63	72.19	3.37	Peridot	3.28–3.38
Amatista	2.65	102.81	56.81	2.24	Purple glass	Variable
Aqqua marina tenera	2.68–2.74	65.31	41.31	2.72	Aquamarine	2.68–2.74
Cristallo	2.65	229.75	143.25	2.66	Quartz (rock crystal)	2.65

[a] *The screened rows refer to simulants.*

[b] *Expected values if the gem names given by Galileo were correct (Dominy, 2013).*

[c] *Fractions have been converted to decimals; in units of Florentine grains (1 grain = 0.5894 gram).*

[d] *Calculated here from the weights in air and water measured by Galileo.*

[e] *Empirical measurements on relevant gem-quality minerals (Dominy, 2013).*

[f] *Values reported are for aquamarine, as there are no typical SG values for heliodor given in the literature.*

LIBRI TRE
DI M. LODOVICO
DOLCE;
NE I QVALI SI TRATTA
delle diuerse sorti delle Gemme,
che produce la Natura,
DELLA QVALITA',
grandezza, bellezza, & virtù loro.

CON PRIVILEGIO.

IN VENETIA APPRESSO
GIO. BATTISTA, MARCHIO
SESSA, ET FRATELLI.

Figure 4: The title page of Lodovico Dolce's 1565 translation of Camillo Leonardi's 1502 book, nowhere showing the name of the true author. This is a typical case of Renaissance-style plagiarism, yet with the very effective outcome of spreading knowledge on gem materials with their proper Italian names.

tenera ('soft' aquamarine) and *cristallo* (quartz). Unfortunately no description of the samples was provided, so their transparency and rough/cut state are unknown. Only indirectly can we infer that all samples were single gems except for *rubini 3* (three rubies measured as a single sample) and *zaffiri 2* (two 'sapphires', actually spinel, again measured together). All the names used by Galileo were the current Italian gem names, which were those given by Lodovico Dolce (1565; Figure 4) when translating Camillo Leonardi's (1502) *Speculum Lapidum* (Mirror of Stones). Dolce's definitions include a description of the colour for some gems (e.g. topazio is a yellow stone), but the colours of several of Galileo's samples cannot be inferred.

The *'diamante'* measured by Galileo was not a diamond at all. He should have guessed this from the start, as the gem weighed slightly more than 48 grains (i.e. 28.3 grams or 141.5 ct), and therefore would have been extremely costly. According to de Boot (1609, pp. 128–132), a *perpolitus, & absque omni vitio* (flawless diamond) of 12 ct—which was considered to be an enormous crystal for diamond at that time—would then sell for 11,600 florins, which was the price of a very large house. A stone like that certainly did not belong either to Galileo or his family. Galileo's own perspicacity should have advised him that the man (a friendly gem dealer, possibly) who had loaned the gem to him either wanted to test his instrument or make a fool of him, considering Galileo too young for such a business. In any case, Galileo measured the stone twice and his data yield a consistent SG of 3.55. This is very close to the SG of OH-free topaz (3.56), which can have a rather similar appearance to diamond. Simulants for diamond were common in Galileo's time, and were well known to gem merchants. The main ones cited at the time were very light coloured sapphire, amethyst, chrysolite and, indeed, topaz (de Boot, 1609, pp. 117–118). All these gems, except topaz, have SG values much different from Galileo's measurements.

The reliability of Galileo's balance is strongly supported by the SG value of the next gem he tested, ruby. His data for *rubini 3* yielded an SG of 4.02, against a theoretical D = 3.989 g/cm^3, which is within the 1% error of determination. A second round of measurements on *rubini 3* gave the same value. By contrast, Galileo's data for another sample called *rubino* gave an SG value of 3.56, which does not fit with corundum, but is consistent with spinel. Most likely, this gem was a *balascio* (balas) or red spinel. *Balas ruby*, as it was sometimes called, was a very popular stone. An additional sample measured by Galileo, consisting of two blue stones named *zaffiri 2* (sapphire), yielded an SG of 3.57, also likely spinel.

It is possible that all the gem samples mentioned so far were from Sri Lanka (then known as Ceylon) or Myanmar (then Pegu), where gem-quality spinel, topaz and, to a wider extent, corundum are well known. Sri Lanka and southern India were the major sources of gems arriving in Europe through the Portuguese maritime trade, which at Galileo's time had ousted the traditional long-distance caravan route through Asia (Vassallo e Silva, 1993). A Sri Lankan origin is also supported by the fact that one of the three 'emeralds' Galileo measured had an SG of 3.07, corresponding to uvite, which is occasionally found together with spinel in the Uva Valley gravel beds (Dunn et al., 1977).

Galileo used the names *zaffiro* and *smeraldo* for blue and green stones, respectively, irrespective of their measured values. However, two green stones did yield measurements giving SG = 2.72, which is within the range of emerald (Dominy, 2013). Another sample with the SG of beryl was referred to as aquamarine, but its description as *'tenera'* (soft) is inexplicable. As for the three samples labelled sapphires, none of them was corundum: one was a blue spinel (SG = 3.57); another was possibly a gahnospinel (SG = 3.83), which is a gem that only recently was encountered in the European market; and the third one (SG = 2.58) may have been either cobalt-blue glass or cordierite (i.e. iolite). All these gem varieties are known from some Sri Lankan basement rocks and related gravel beds (Oltean et al., 2011; Gorghinian et al., 2013). They additionally support Sri Lanka as the possible origin of some gems available in Europe during the Renaissance, although we cannot rule out the possibility of their coming from elsewhere in southern Asia.

The case of Galileo's yellow *topazio* is rather peculiar. None of the three *topazio* stones weighed by Galileo met the SG requirements of topaz: two appear to have been beryl (SG = 2.75), in the yellow variety that came to be known as heliodor in the early 20th century, and the other one apparently was citrine, the yellow variety of quartz (SG = 2.66). At that time, citrine was the most widespread yellow gem available, as it was found sparsely in the Bohemia-Saxony silver-bearing ore district. Notably, true topaz was also well known there, and was commonly mistaken for citrine if yellow or for diamond if colourless (i.e. *Adamas Bohemicus:* Bohemian diamond; de Boot, 1609, p. 219).

Quartz (*cristallo,* i.e. the colourless variety known as rock crystal) was measured by Galileo with amazing precision (SG = 2.66 versus D = 2.655 g/cm^3). The *calcidonio*, with SG = 2.61, fits well into the highly variable properties of chalcedony, which is always less dense than macrocrystalline quartz because of its porous texture. By contrast, Galileo's *amatista* was by far too light (SG = 2.24) to be amethyst; it may have been purple glass. It appears that one of his *crisolito* (chrysolite) samples was also glass, with a relatively low SG of 2.48. Glass imitations are known from Roman times and were not uncommon during the late Middle Ages, where the production of glass of various colours and forms had advanced considerably although only by empirical methods (O'Donoghue, 1997). Notably, not all *crisolito* samples measured by Galileo were imitations. Indeed, two of them had SG = 3.37, which is consistent with olivine that is intermediate in the forsterite-fayalite series (i.e. peridot).

At the time of Galileo one would already easily distinguish between massive dark blue lapis lazuli and light blue *turchina* (turquoise), which displays variable specific gravity due to its porous texture (for Galileo's samples, SG = 2.73 and 2.77). One would also be able to distinguish garnets from other red stones (Gilg, 2008), although there was not yet knowledge that garnets constitute a large group. Indeed, Galileo used *granata* (garnet) to refer to a stone that, on the basis of its SG value (3.61) might have been the orange hessonite variety of grossular, and also to another sample that could have been pyrope-almandine (SG = 3.98). In the same way, he was unable to distinguish between pearls from what were later known to be from a *Pinctada sp.* mollusc (SG = 2.59) and a *Strombus sp.* gastropod (i.e. conch; SG = 2.88).

Conclusion

Within the framework of late Renaissance gemmology, Galileo was unique as a scientifically inclined researcher, which also made him a pioneer for all Western Europe. At his time, almost all treatises on minerals and gems consisted of the mere description of a number of stones from the viewpoint of a traditional set of external characteristics such as colour, shape, transparency and hardness. Most often, this objective information would be provided with remarks on their mysterious properties, mostly of a mystical nature, which had been passed down from the Middle Ages (Mottana, 2006). Galileo introduced a scientific measurement that, eventually, would prove to add significantly to the characterization of minerals and gems (e.g. Figure 5).

In actuality, the young Galileo had no idea about specific gravity as a property of materials, nor had he developed systematic thought about it: he only conceived an instrument appropriate

Figure 5: The Medici coat of arms, a Florentine artwork made in 1590–93 that originally decorated the front of the disassembled cabinet of grand duke Ferdinand I (1587–1609). It provides a good example of the need for scientific gemmology to be applied to historical jewels. The faceted 6 × 4 × 2 cm stone was originally believed to consist of a 'topaz of Spain' (citrine), and was set with six half-spheres of rock-crystal (four had backs painted in red, one in blue and one was left unpainted). The half-spheres simulate rubies, a sapphire and a diamond (Heikamp, 1963). The faceted stone was recently re-identified as a smoky quartz (Fantoni and Poggi, 2012, p. 54, Fig. 1). This artwork is preserved as Inv. 13201 in the historical collection of the Museo di Storia Naturale, Sezione di Mineralogia e Litologia, Università di Firenze. Photo by Saulo Bambi.

to determine if Archimedes could accurately test the composition of objects made by two alloyed precious metals, and extended its use to gem materials. He did not even describe the gem materials he measured, but apparently only took for granted the names provided by the merchant(s) who loaned or sold the samples to him, with only the precaution of checking their spelling against Dolce (1565), which was the gemmological reference book in Italian of his time (again, see Figure 4).

Galileo's hydrostatic balance was a valuable scientific innovation for Europe, where the Arabic studies on hydrostatics applied to gem materials had not filtered in yet. However, the new instrument did not continue to be used for testing gems, since neither Galileo himself nor any of his pupils and followers did so with a consistent methodology. There were indeed hydrostatic essays made and reported by innovative scientists such as Simon Stevin (1586) in The Netherlands, Gian Battista Della Porta (1589) and Marino Ghetaldi (1603) in Italy, and Francis Bacon (quoted in Davies, 1748, p. 421) in Britain in the early 17th century, but they mostly used metals for their experiments. Consequently, Robert Boyle is credited for the most significant 17th-century gemmological treatise, which includes considerations of specific gravity (Boyle, 1672).

One reason for the neglect of Galileo's attempt at testing gem materials by the hydrostatic method may be that the possible users (i.e. gem merchants) would have considered it slow and confusing. Indeed, gemmology continues to wrestle with this problem: being a branch of applied mineralogy, it must always balance the requirements of science with those of the business of gems.

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