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**Bronzes Dorés:**
*A technical approach to examination and authentication of French gilt bronze*

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Abstract

Creations in gilt bronze were of tremendous importance to the French decorative arts, particularly from the late 17th century through the early 20th century. The materials, methods and aesthetics behind their production share a great deal in common with fine art sculpture of the period. This paper provides an overview of several methods used at the J. Paul Getty Museum for the technical and scientific study of gilded bronzes. These include the study of chasing and gilding techniques, the evidence revealed on unfinished surfaces as well as X-radiography and elemental analysis by X-ray fluorescence (XRF) spectroscopy. The complexities and difficulties associated with each approach are discussed, and an argument is made for drawing conclusions based on the preponderance of evidence from all methods. Particular attention will be given to the Getty’s long-term research programme of elemental analysis.
**Introduction**

Creations in gilt bronze were of tremendous importance to the French decorative arts, particularly from the late 17th century to the early 20th century. The materials, methods and aesthetics behind their production share a great deal in common with fine art sculpture of the period. Much has been written about the evolution of style, economic and historical context, and methods of production of French gilt bronzes (Mestdagh and Lécoules 2010; Ottomeyer, Pröschel, and Augarde 1986; Verlet 1987; Chapman 1993; Considine and Jamet 2000), and in the last decade several collection catalogues have been produced with an emphasis on gilt bronzes (Alcouffe et al. 2004; Wilson et al. 2008; Dupuy-Baylet 2010). Relatively little has been written to date about methods of technical examination specifically focused on gilt bronze, and this paper attempts to provide a brief introduction to the subject based on the last decade’s experience in the Decorative Arts and Sculpture Conservation Department of the J. Paul Getty Museum.

The technical study of gilt bronze at the Getty has been a multifaceted enterprise. Several methods have been used in consort, each contributing to a fuller understanding of the object in question. It has become abundantly clear that no one method can be depended upon to provide a definitive answer to questions of origin, attribution or authenticity.

Rather, a thorough technical evaluation normally includes close examination of the gilded and chased surfaces as well as the unfinished versos of the cast elements, X-radiography, and elemental analysis by X-ray fluorescence spectroscopy (XRF).

Twelve years of elemental analysis at the Getty has produced a dense set of compositional reference data, and preliminary statistical analysis of the dataset has proved useful for purposes of authentication and dating. This work suggests that international collaboration in the quantitative and statistical study of copper alloy compositions in works of art could lead to many significant discoveries and should be actively promoted.

**Chasing**

The French decorative arts collection of the J. Paul Getty Museum offers several examples of gilt bronze that are particularly instructive for the study of chasing and surface finishing. As much of the collection, particularly the furniture, has been
subjected to extensive technical and scientific study (Wilson et al. 2008; Wilson and Heginbotham Forthcoming), many of the gilt bronzes have been securely authenticated, while others are known to be later copies, legitimate replacements or frauds. In several instances, these later gilt bronze elements, dating from the 19th, 20th and even 21st centuries, are present in the collection alongside original 17th- or 18th-century examples of the models on which they were based. Close examination of these pairings can be very instructive, as the examples below will attempt to demonstrate.

Figure 1. An original baroque gilt bronze on the left compared with a later surmoulage copy on the right. Both are from a pair of baroque pedestals c. 1700 attributed to André Charles Boulle in the collection of the J. Paul Getty Museum (acquisition no. 88.DA.75.1-2). It could be said that the late 19th- or 20th-century copy on the right is much too finely and “mechanically” chased in comparison to the early 18th-century original.

The evaluation of chasing and surface finishing is a delicate matter that relies heavily on the experience and judgement of the viewer; that is to say, it is a matter of connoisseurship. There are several clear temporal trends in chasing related to style and technique that are often taken into account when evaluating gilt bronze (Garnier and Chouartz 1903, 6–8; Verlet 1987, 370–89). In the broadest (and admittedly simplistic) terms, one might say that baroque gilt bronzes tend to be loosely and expressively chased with relatively coarse textures. Rococo examples tend to be somewhat more delicately chased but still retain a certain lively variety of textures, with considerable emphasis on the interplay between matted and burnished areas. Overall, the neoclassical period is defined by a movement towards very fine, almost jewel-like chasing that is sometimes accompa-
nied by chemical matting treatments. Chasing associated with 19th- and early 20th-century revival styles, when well executed, are sometimes described as “outdoing” their 18th-century progenitors with overly zealous and, some would say, excessively mechanical chasing that misses the expressiveness of earlier periods.

In the Getty collections, these heuristic models are sometimes borne out. Two masks from a pair of baroque pedestals (c. 1700) attributed to André Charles Boulle (JPGM acquisition number 88.DA.75) in the collection of the J. Paul Getty Museum provide an excellent example. Figure 1 shows a detail of an original baroque gilt bronze on the left compared with a later copy on the right that one might say is “too well chased” for the period it seeks to imitate. The copy is clearly a direct surmoulage of the original (see “Unfinished surfaces” below), and almost certainly dates to the very late 19th or 20th century based on its alloy (For a more detailed discussion of the mounts and the pedestals from which they come, see Wilson et al. 2008, 228–35)

Figure 2. On the left, a detail of an original rococo gilt bronze from a commode by Joseph Baumhauer c. 1755 (JPGM acquisition no. 55.DA.2); and on the right, a mid-19th-century interpretation of the same model from a commode stamped Delorme (JPGM acquisition no. 70.DA.79). Note the lively contrast of matte and burnish in the original in comparison to the relatively flat and undifferentiated textures of the 19th-century copy.

Another example of this type can be found when one compares the exquisite rococo mounts of a commode by Joseph Baumhauer (c. 1755, JPGM acquisition number 55.
DA.2) with those of the same model from a commode once thought to be 18th century, but which technical study has shown is more likely to date to 1850–1880 (JPGM acquisition number 70.DA.79) (For a more detailed discussion of the mounts and the commodes from which they come, see Wilson and Heginbotham Forthcoming). Figure 2 shows the lively contrast of matte and burnish in the original in comparison to the relatively flat and undifferentiated textures of the 19th-century copy. Unlike the Boulle masks, the later mounts were not made by surmoulage. The differences in form and dimension are significant enough that they must have been made from new foundry models that were produced based on drawings or photographs of the originals.

Figure 3. An original bronze from a commode c. 1740 by Bernard van Risenburgh II (JPGM acquisition no. 72.DA.42) on the left, compared with a late 19th- or early 20th-century replacement from another commode by van Risenburgh (JPGM acquisition no. 65.DA.4) on the right. One might be forgiven for considering the original to be excessively and mechanically chased, while in fact, a more correct interpretation might be that the reproduction has not been as skilfully finished as the original.

In some cases, however, general rules of thumb prove to be less reliable. The Getty collection contains two fine commodes in Asian lacquer by Bernard van Risenburgh II, both dating to around 1740. The two commodes, in red Chinese lacquer (JPGM acquisition number 72.DA.42) and in black Japanese lacquer (JPGM acquisition number 65.DA.4), both share many mounts of the same model. A comprehensive technical study of both pieces, including elemental analysis of the gilt bronzes, has shown quite conclu-
sively that all the gilt bronze mounts of the latter have been replaced, either in the late 19th or early 20th century (see “Elemental analysis” below). However, looking at the two groups of bronzes side by side (see Fig. 3), one might be forgiven for considering the original to be excessively and mechanically chased, while in fact a more correct interpretation might be that the reproduction has not been as skilfully finished as the original.

In still other cases, reproduction gilt bronze elements can be virtually indistinguishable from originals. This may be particularly common where the pieces in question are not highly finished. Two other furniture mounts by van Risenburgh illustrate this rather well. The original mount, though securely attributed to this very fine maker (the writing table to which it belongs is JPGM acquisition number 70.DA.85) is not highly finished and neither is the surmoulage reproduction of it found elsewhere on the same piece (see Fig. 4). Of course, there are slight differences between the two, but they are so nearly identical that no heuristic aid could point with confidence to the original based solely on interpretation of the chasing.

Figure 4. A surmoulage copy on the left and an original mount on the right, neither highly finished, from a van Risenburgh writing table c. 1750 (JPGM acquisition no. 70.DA.85). The two are nearly identical in their surface finish.

In summary, connoisseurship of the chasing and finishing of gilt bronze surfaces is an important component of a technical examination and can focus attention on differences and incongruities between gilt bronze pieces or elements. However, it is the experience of the author that the enterprise is not without its hazards, and first impressions are not always borne out by further technical study.
Unfinished Surfaces

Careful examination of unfinished surfaces (typically the back or interior) can often reveal copies made by surmoulage, that is to say, copies made by taking moulds directly from original gilded bronzes. Evidence of this practice is usually found by looking closely at the marks of files, chisels and drills used in “cold work” to shape the metal after casting. In general, foundry models for traditional sand casting during the ancien regime will have relatively little cold work in comparison to finished works. Foundry models of the 18th century often seem to have been made of brass; see for example the 1715 Acte de Delaissement and the 1732 Inventaire après Deces of André-Charles Boulle in which the vast majority of models are listed as “bronzes” (reprinted in Samoyault 1979, 71, 135–47). This seems to have been the case through the early 20th century as well (see for example Payne 2003, 325–65). Lead, plaster, terracotta and wax models are also frequently mentioned in the archival and modern literature. There are two reasons for this; first, there was little incentive to thoroughly chase or finish a foundry model since fine detail is likely to be lost during casting; secondly, foundry models never have to be assembled into a finished piece, a process that often requires considerable cold working. Fitting gilt bronze mounts to a piece of furniture, for instance, is a laborious process that can require substantial bending and filing to ensure that the metal conforms closely to the wooden substrate. Finished gilt bronzes of all forms are often composed of multiple castings that, similarly, must be bent and filed to assure that adjacent castings fit together seamlessly. Tool marks from cold working are typically crisp and smooth. If a mould is taken from a cold-worked casting and a duplicate is cast, or if an original casting is used directly as a foundry model, the tool marks will also be reproduced, but they will have a slightly rougher “as-cast” surface that is normally distinguishable upon close inspection or with the aid of low power magnification.

Figure 5 shows details of the versos of the castings shown in Figure 1. The original early 18th-century gilt bronze (with its clearly defined file marks) is on the left and the
surmoulage (with its soft and rounded impression of the file marks) on the right. While it is not beyond the realm of possibility that an original 18th-century mount could have been made as a surmoulage, it must be considered unlikely. Indeed, this kind of evidence raises suspicions and should normally lead to a careful comparative examination of the chasing of the two mounts as well as analysis of their respective elemental compositions.

It is interesting to note the triangular punch marks seen on the right in Figure 5. These were almost certainly added by the chaser of the reproduction to add “tooth” to the back surface so that the mount would grip tightly to the pitch substrate commonly used to secure castings during chasing. It seems that this type of “toothing” of the backs began to be common in the late 18th century and continued to be practised throughout the 19th century.

Examination of the unfinished surfaces can also reveal other evidence regarding methods of production. The majority of French gilt bronze has been produced by sand casting. Unfinished sand cast surfaces are generally granular, but fairly smooth with relatively few flashes (thin fins of metal protruding from the casting that occur when hot metal flows into fractures in the mould during casting) and no bubbles of metal on the surface (see Fig. 6). In many cases, sand castings appear to have been executed in two-part moulds (Considine and Jamet 2000). However, for high relief and deeply undercut castings, there appears to be evidence that rather complex piece-moulded sand casts were also being produced, probably as early as the late 17th century (Y. Chastang, personal communication, May 2013), and certainly by the middle of the 18th century. Mould lines evident on unfinished surfaces such as those seen in Figure 6 are generally the best evidence that this technique was used.
Traditional lost wax casting also seems to have been used with some regularity for French gilt bronzes, primarily for hollow castings of figural or otherwise highly three-dimensional forms. Prior to the advent of ceramic shell casting for sculpture in the late 1960s (Silver 1968), lost wax casting was usually done using a plaster-based investment material. Plaster moulds are substantially more prone to cracking from thermal shock during casting than are sand moulds. Thus, the presence of numerous, irregular flashes on unfinished surfaces is commonly considered a sign of lost wax casting. In addition, in the traditional lost wax method, plaster-based core material was often poured into the hollow interior of the wax model and this was allowed to solidify in place. Not infrequently, small bubbles of air could be trapped on the surface of the wax when the plaster was poured. After the wax was burned out and the metal cast, these bubbles in the plaster could become filled, creating raised bubbles of metal on the interior of the casting. The presence of these small bubbles of metal on unfinished surfaces is thus another easily observable indicator of lost wax casting (see Fig. 7).

Figure 7. Irregular flashes (left) and small bubbles of metal (right) are the most easily observed evidence of lost wax casting (both castings are from figural elements on the corner cabinet c. 1750 by Jacques Dubois, JPGM acquisition number 79.DA.66).

Examination of the verso can also yield clues to the manner of gilding on the recto. For instance, beginning in the mid-1840s, electroplating began rapidly to replace mercury amalgam gilding (Craddock 2009, 86). Because pieces to be electroplated were submersed in a plating tank, a resinous or bituminous “resist” was commonly applied to unfinished surfaces in order to prevent unnecessary and wasteful application of gold to surfaces that would never be seen. Such resists are often left in place on legitimate productions of the late 19th and early 20th century, though they are typically removed from earlier pieces that have been re-gilded by electroplating, or pieces that have been produced with the intent to deceive. Figure 8 shows a typical electroplating resist varnish on a gilded bronze mount produced for The Elms by Allard et ses Fils of Paris in about 1901, now in the collection of the Preservation Society of Newport County, Rhode Island. The Elms, completed in 1901, was modeled after a mid-18th century French chateau. It was purchased in 1962 by the Preservation Society of Newport County and in 1966 was designated a National Historic Landmark. The mount adorns a massive marble urn flanking the base of the main staircase.
From time to time, gilt bronze elements produced by electrotyping, also known as galvanoplasty, can be found. This is an extremely high-fidelity reproductive technique invented in about 1838 and used widely in the 19th century (Blum and Hogaboom 1924; Heinrich 1938). It was particularly favoured, it seems, for reproducing (often legitimately) the highly detailed and finely chased gilt bronzes of the late 18th century, though gilt bronzes of all periods could be reproduced in extraordinary detail. The process of electrotyping is often used to form a rather thin “shell” of pure copper (on the order of 1 mm thick) rather than a solid form. Many different metals could be used to create electrotypes, notably gold and silver, but reproductions of gilt bronzes seem mostly to have been executed in copper and then gilded. Since the shell can be fragile, it is the author’s experience that electrotypes were often backfilled with cast brass or another metal. Figure 9 shows the verso of a high quality electrotype from the late 19th century: the “neo-Boulle” wall cabinet to which this electrotype belongs is in the collection of the Preservation Society of Newport County (PSNC.344.2). Note that the edges of the copper shell are slightly raised and pronounced, and the brass backfilling, which was simply poured from a ladle into the back of the open copper form, is rough and flat. Identification of electrotypes can be confirmed by XRF on the recto; this will normally detect only copper and gold (no zinc, tin or lead), with possible minor peaks from mercury and silver associated with the gilding.
Figure 9. A legitimate electrotype reproduction c. 1890 of a Boulle mask from the late 17th century. The late 19th-century “neo-Boulle” wall cabinet to which this electrotype belongs is in the collection of the Preservation Society of Newport County (PSNC.344.2). Note that the edges of the copper shell are slightly raised and pronounced, and the cast-in brass of the back is rough and flat.

**X-Radiography**

To date, X-radiography has been employed only sporadically in the examination of gilded bronzes at the J. Paul Getty Museum. Most gilt bronze forms are cast in such a way that the unfinished surfaces are visible and, therefore, general determinations about the casting technique can be made without recourse to X-radiography. In the case of more sculptural and figurative lost wax castings, naturally, X-radiographs can prove to be quite enlightening (The techniques for their interpretation are addressed in Bassett and Bewer 2014). One additional avenue of inquiry that may prove to be of value concerns the X-radiographic study of joints in solid castings such as candle arms. In several instances, X-radiographs of 18th-century works in the Getty collection show that long and sinuous candle arms were often cast in short, solid sections that were subsequently joined together. One common method seems to have been to drill pilot holes into the ends of the two sections to be joined and then tap the holes with threading. A threaded rod was then inserted into the holes and the pieces were twisted together until they nearly joined at the centre. The pieces were then rotated into proper alignment and the small gap between filled with molten brass solder. These joints were then filed, chased and gilded and are therefore often completely invisible to the naked eye, even to this day.
X-radiography can, however, reveal the joints in great detail (see Fig. 10). In fact, the resolution and detail can be sufficient that quite precise measurements can be made of the diameter of the drilled hole, the diameter of the threaded rod, and the spacing or “pitch” of the threads, taking into account any enlargement of the image engendered through the imaging process. Since there were no common standards for the relative dimensions of drills, rods and threading in the 18th century, it is at least conceivable that the specifications of the tools and materials used in different workshops could be identified and that X-radiography could then be used for attribution of certain forms of gilt bronze. For this possibility to be realized, of course, a large number of well-documented works from different workshops and periods would have to be analysed, presumably by several institutions over a period of many years, and the results brought together into a shared database. As X-ray computed axial tomography (CAT) scanning becomes more available to arts institutions, it may become practical to make very high precision measurements of more detailed features as well, such as the thread profiles and the shape of the drill bit used for the pilot holes.

Figure 10 Detail of an X-radiograph of a candle arm from a wall light dated 1756 by François-Thomas Germain in the collection of the J. Paul Getty Museum (JPGM acquisition no. 81.DE.96). The threaded fastener used to join two separately cast sections is clearly visible.
Elemental analysis

Description of the project

Elemental analysis of gilt bronze objects has been a subject of ongoing study at the Getty Museum for approximately 12 years. The analytical technique of choice has been XRF and the majority of the data has been acquired using portable, handheld instruments. The advantages as well as the non-trivial limitations of this technique have been addressed at length elsewhere (Heginbotham et al. 2011; Shugar 2013; Smith 2012) and will be addressed further below, but suffice to say that XRF is a very attractive choice for studying artworks as it is a non-destructive method that can provide rapid multi-element quantitative analysis with detection limits of around 0.05% (depending on the element of interest as well as the instrumental and procedural parameters chosen). The analytical programme at the Getty has focused primarily on the composition of the base metal used for French castings; data have also been regularly collected on the composition of soldering metal, sheet metal (such as that used for Boulle marquetry, hinges, locks, etc.) and on the composition of gilt bronzes from other countries, particularly England.

Analyses for alloy composition have been performed primarily on ungilded surfaces that have been cleaned only with a stiff, natural bristle brush; in cases where the surface is unusually dirty or is contaminated with traces of gold, a glass bristle brush has been used to prepare a clean surface for analysis.

The data compiled to date have yielded considerable insight into the working methods and materials of French bronziers and has proved to be of considerable utility for the evaluation and authentication of gilt bronzes in the Getty collection. Some forays have been made into sophisticated statistical analysis of the data generated with promising results and further work in this direction is anticipated. It has also become abundantly clear that meaningful interpretation of the quantitative results depends very strongly on an understanding of the history of both artistic technology and metallurgical technology. That is to say, the numbers alone may suggest a trend, but confidence in the significance and reliability of the trend comes only if it can be explained through a historical and technological context. The discussion below cannot be comprehensive, but rather is designed to give selected examples of findings and their contextual interpretation in order to introduce the research methodology that we are following.

The XRF studies at the Getty have focused on the period from 1675 to the present, and thus far, the data gathered include the results of approximately 1300 XRF analyses of discrete components belonging to approximately 250 different objects. We have attempted to include analyses of as many securely provenanced and dated objects as possible from throughout the time period studied. To this end, over 500 of these compositional analyses (representing individual components of approximately 120 objects) of Parisian casting metal can be considered “reference material”; that is, material whose date of production in Paris is known within a period of 20 or so years to a high level of confidence. This relatively large dataset of reference analyses has become extremely valuable as a point of reference when evaluating gilt bronzes of uncertain provenance.
The collection of the J. Paul Getty Museum contains many examples of securely authenticated French gilt bronzes of the late 17th and 18th century, but many fewer objects from later periods. The author has thus depended on, and benefited greatly from, the generosity of many other institutions and private individuals who have granted access to objects, particularly of the 19th and 20th centuries for analysis by XRF. These include Adrian Alan, Atelier Michel Jamet, Yannick Chastang, Doheney Mansion, the Fine Arts Museums of San Francisco, Institut National du Patrimoine, Musée Carnavalet, Musée des Arts Décoratifs, Christopher Payne, the Preservation Society of Newport County, the Royal Collection, the Victoria and Albert Museum and the Wallace Collection.

XRF analysis of copper alloys, as currently practised at the J. Paul Getty Museum, returns compositional data for 13 elements. For the purposes of discussion, these can be divided into two groups: the so-called “major” and “minor” elements (There is no clear consensus in the literature regarding the definition of terms such as “major”, “minor” and “trace” for analysis of this sort. The meanings used here are relevant only to the present context). For gilt bronzes, the concentrations of the major elements – copper, zinc, tin and lead – serve to define the casting alloy, and they are all generally present in the casting metal in amounts greater than 1% by weight. They are also all elements of which the founders, particularly in the 18th and 19th centuries, would have been aware and the founders would likely have had significant control over their concentrations in the metal with which they worked. The additional minor elements are generally present in amounts less than 1%, and importantly, are elements that founders normally would have had little influence over since they are essentially impurities that reflect the level of smelting and refining technology at the time the metal was produced, as well as the origin and nature of the ore used to produce the metal. The minor elements referred to in the discussion below include (in order of atomic weight) manganese, iron, cobalt, nickel, arsenic, silver, cadmium, antimony and bismuth. The analysis of aluminium, silicon, phosphorus and sulphur requires that analysis be conducted in a vacuum or in a helium-flushed environment. These elements have therefore not been studied to date at the Getty. There is, however, a strong argument to be made for their study as the first three in particular appear in many modern alloys, though never, as far as is known, in 18th-century castings. For a more detailed discussion on the significance of different elements (Pernicka 1999).

Observations on the alloys used

In terms of the major elements, certain observations about the preferred alloy for French gilt bronzes can be made based on the analytical results. In virtually all of the French gilt bronzes analysed by XRF for this study, the alloy of the casting metal can be described as brass, that is to say, an alloy dominated by the presence of copper and zinc. From the late 17th to the mid-19th century, the dominant type of casting brass analysed had a moderate zinc content ranging from about 13% up to about 25% (see Fig. 11), and usually contained between 0.5% and 2% of both tin and lead. The reason that this composition range seems to have been rather stable over time probably has to do with
the number of different processes and working techniques that were involved in the production of gilt bronze objects (Verlet 1987, 152–79; Chapman 1993; Considine and Jamet 2000).

Each process – from casting, to soldering, to chasing, to gilding and fitting – placed certain demands on the properties of the alloy, and the final composition had to perform well at each stage of the process. This perspective is thoroughly discussed and illustrated in Jean-Pierre-Joseph d’Arcet’s Mémoire sur l’art de dorer le bronze published in 1818 (Arcet and Sève 1818, 8–18). D’Arcet questioned founders, chasers, turners, and gilders, providing them with various copper-based alloys, and asking them to rank the mixtures according to how well they performed for their work. Perhaps not surprisingly, of the eight alloys ranked by all the artisans, the only alloy to receive ratings of “très-bon” from all four was one that contained 18% zinc, 3% tin and 1.5% lead, quite close to the alloys found in the Getty’s study programme. This also appears to fit well with what d’Arcet says was the founders’ typical practice of preparing their casting alloy: “Nous avons vu que les fondeurs emploient ordinairement 75 de cuivre jaune et 25 de cuivre rouge étamé et garni de soudure” We have seen that the founders use normally 75 parts of brass [about 28–33% zinc] and 25 of copper, tinned and coated with solder [presumably lead-tin solder] (Arcet and Sève 1818, 12).

D’Arcet makes many interesting observations regarding the properties deriving from each of the constituent elements. For instance, he states that the proportions of tin and lead in the aforementioned alloy may be reversed to advantage for small castings as the lead will make the melt flow more easily, although the casing will be more prone to cracking (“moins de la ténacité”). He notes further that too much lead makes the gilder’s
work difficult; too much tin results in an alloy that is too hard and therefore difficult to chase, while too little tin makes the metal too soft for the chaser and too viscous (pâteux) for the founder. D’Arcet also reports that he analysed two samples of the alloy preferred by the famous bronzier Pierre-Philippe Thomire and found them to contain about 23% zinc, 2% tin and 3% lead. All of these alloys, discussed by d’Arcet, accord well with the analytical results found for securely provenanced gilt bronzes of the 18th century, the vast majority of which contain 15–25% zinc with small amounts of tin and lead.

It is important to note that many gilt bronzes are assembled by soldering together several individual castings. Therefore, an additional critical factor for the selection of a casting alloy that is not mentioned by d’Arcet is that it must be able to be ‘safely’ soldered. At least until the widespread introduction of powerful blowpipes in the 19th century, the vast majority of soldering would have been accomplished by placing hot charcoal pieces on and around the joint, with solder and flux in place, and heating until the solder melted and fused the joint. This means that there must be an appropriate soldering metal available that has a melting point sufficiently below that of the casting metal to allow the solder to be melted without danger of melting the castings themselves. The solder must also be strong enough to withstand the stresses of chasing and fitting; this would rule out the low-melting, lead-tin type solders. In addition, the solder should be similar in colour to the cast alloy, and must receive gilding in a manner similar to the castings, making silver solders unsuitable. Silver solders were typically made from approximately two parts of silver mixed with one to two parts of brass or copper (Salmon 1685, 244–45). In the author’s experience of analysing solder joins, it appears that the universal soldering metal use in France to assemble gilded bronzes in all periods is a brass with a zinc content significantly higher than the casting metal. For example, a brass solder with 30% zinc will melt at a temperature about 60 °C lower than a similar casting metal with 20% zinc (Gillett and Norton 1913). Based on the author’s experience, it seems that 18th-century metalworkers typically used solders with 10–15% greater zinc levels than the casting metal that they were joining, and the resulting temperature differential seems to have been satisfactory to ensure safe soldering.

Gilding

XRF analysis can provide some useful information regarding the presence and method of gilding used in the production of gilt bronze objects, though the results can rarely be considered conclusive. First of all, the detection of substantial amounts of gold can confirm, naturally, that an object has been gilded. This is not necessarily as trivial a finding as it may seem since it was not uncommon in the 18th century to apply durable tinted varnishes to chased and polished castings, creating the appearance of gilding for a fraction of the cost. There are instances where even an experienced eye may have difficulty telling the difference, particularly on dirty and corroded pieces. XRF analysis can also give a reasonably good indication of whether a piece has been gilded by traditional mercury amalgam gilding or by electroplating. In the author’s experience, amalgam gilding generally results in a considerably thicker layer of gold than electroplating, and the presence of mercury is virtually always detectable in the spectrum.
While methodologies exist for measuring the thickness of gilding layers (Karydas 2007; Cesareo et al. 2009; Chiojdeanu, Cristea Stan, and Constantinescu 2011), there has been no systematic study to date on the thickness of historic gilding layers according to method of application. In addition, the presence or absence of mercury may be an ambiguous indicator since mercury pre-treatment was sometimes used prior to electroplating (Reid and Goldie 1974) and the amount of mercury present in amalgam gilding decreases with the time and temperature of firing (Anheuser 1997).

**Diachronic trends**

Several diachronic or temporal trends can be noted for major elements in the XRF reference data collected so far in this study. For example, one immediately apparent observation that can be made is that there is a general upward trend in the zinc concentration through time (Fig. 11). This is a trend that has been observed by many others in temporal and geographic contexts far wider than those covered by this study (Cameron 1974; Caple 1995; Glinsman 1997). In broad terms, this is probably associated with metallurgical developments that allowed the production of progressively higher zinc levels in brass at progressively lower costs through time. Specifically, there were gradual improvements in the efficiency of the traditional cementation process of brass production, at least up until the beginning of the 19th century. While the cementation process (in which zinc carbonate or oxide is mixed directly with copper and charcoal in a cementation crucible) is technically capable of producing brasses with very high zinc contents of 40% or more (Welter 2003; Bourgarit and Bauchau 2010), it seems that standard industrial practice limited the content, probably to around 28 or 30% early in the period under discussion, rising up to around 33% in the latter 18th century (Percy 1861, 1867; Day 1990; Newbury, Notis, and Newbury 2005). Spelter brass with even higher zinc content (produced using zinc metal) had been available for centuries, but only at very high cost and its use was severely limited. By the middle of the 18th century more spelter brass seems to have been available in Europe due primarily to the production of zinc in England and the importation of zinc from China (Day 1991; Craddock and Zhou 2003). By the early 19th century, production of spelter brass became economical on a large scale on the continent allowing widespread production of brass with essentially unlimited zinc content (Gibbs 1958; Day 1991). In the first half of the 19th century, speltering gradually replaced cementation, so that the last European cementation brass production of any significance occurred around 1850 (Percy 1861; Tylecote 1976).

While these developments probably contribute to the general rise in zinc levels observed in Figure 11, it is important to note that the zinc composition of the casting brass tracked by XRF does not approach the limits of the technology at any given period. This is not surprising if one considers the prudent margin of safety for soldering discussed above. In fact, it may have been the rising amount of zinc that was available in solder that allowed the amount of zinc used in casting metal to rise steadily over time, while still maintaining a steady separation of zinc content on the order of 10–15%.

Additional temporal, or sometimes geographic, trends can be observed in most of the other major and minor elements included in the Getty study. In virtually every case, the trends can
be explained through understanding their metallurgical and historical context. For instance, it appears that average iron levels in French casting brass declined rather abruptly during the first half of the 19th century. This coincides well with, and is probably explained in large part by, the industrial transition in Europe from cementation brass to spelter brass, although not everyone agrees that the evidence for this is entirely clear (Bourgarit and Thomas 2012). Even in the late 18th century, it had been noted that spelter brass contained less iron than cementation brass and was therefore less magnetic and more suitable for the production of compasses (Watson 1786). It is thought that the calamine used in the production of brass by cementation could often have significant iron impurities that could be transferred into the brass whereas the use of pure zinc metal obviated this (Day 1990). One consequence of this trend is that a strong rare earth magnet will often stick to castings made before about 1850, while this is rarely the case for later castings. The author is indebted to Robert Van Lange for sharing his observation of a similar phenomenon in bronze sculpture. It should be stressed however, that this should not be considered to be a reliable test and, in particular, there will be instances where rare earth magnets do NOT stick to pre-1850 brass castings.

![Figure 12 Nickel content plotted against time based on 539 XRF analyses of securely dated individual French gilt bronze castings.](image)

Other trends apparent in the data include the rather sudden appearance of a certain number of castings with elevated nickel levels (up to about 1%) in the late 19th century, a phenomenon that persists into the 21st century (see Fig. 12). During the early part of this period, the occurrence of elevated nickel may reflect the discovery in the 1870s of huge new copper ore fields in the Sudbury area of Ontario in Canada. The Sudbury ore contained significant levels of nickel that was very difficult to remove from the smelted copper. A great deal of energy was expended in developing methods to extract the nickel, but nonetheless there was a considerable production of copper with elevated nickel until after World War II when the last smelter handling Sudbury ore converted to electrolytic,
refining (Newton and Wilson 1942; Clow 1992; Lynch 2002). Another development may also have contributed to the occurrence of elevated nickel levels, particularly after World War I. This is the intentional introduction of nickel into certain standardized casting alloys such as the Unified Numbering System (UNS) C85000 series of designations for casting brass alloys. These are specified to contain from 0.2% up to 1.0% nickel, (Copper Development Association, Inc. 2012) apparently for the purposes of reducing the interval of solidification and to induce a finer dendritic structure in the castings (J.-M. Welter, personal communication, April 2012).

**Statistical analysis**

As can be seen in Figures 11 and 12, the XRF results for verified reference castings have grown over the last 12 years to be a reasonably dense and well-distributed dataset. Similar graphs have been prepared for the other 11 elements for which XRF analysis has been conducted, and detailed contextual interpretations of temporal trends in the compositional reference data have been developed. With a 13-dimensional dataset of this size, it becomes challenging to combine the information contained in the results for each element into a single evaluation method when analysing gilt bronzes of unknown provenance. Happily, as the quality and comprehensiveness of the dataset grows, one is able to employ a variety of multivariate statistical methods such as multiple regression analysis (MRA) and principal component analysis (PCA), designed to probe complex datasets such as this. One statistical method that seems very promising for use with this dataset is linear discriminant analysis (LDA). With this method, the reference dataset can be broken up into groups of results clustered by their date of production. Each group is then characterized statistically using the compositional data for all 13 elements and a mathematical model is constructed that defines each group in a manner that maximizes the separation of the groups. XRF results from unknown objects (elemental concentrations for 13 elements) can then be fitted into the model and a calculation can be made that gives the relative probability that the unknown object belongs to any of the defined temporal groups. Figure 13 shows the results of an LDA performed using chronological reference groups to evaluate the gilt bronze mounts from the black lacquer commode by Bernard van Risenburgh II (JPGM acquisition number 65.DA.4) discussed above and featured in Figure 4. Although the commode itself dates to c. 1740, the analysis shows that the gilt bronze mounts that are currently on the piece have only about a 2% chance of belonging to that period. Rather they are most likely (nearly 40%) to belong to the period 1876–1900, though membership in other temporal groups is also possible. In this instance, most temporal groups have been designated arbitrarily as 25-year periods corresponding to quarter centuries while one group (1825–1874) was defined as a 50-year group because of the relatively low number of reference analyses available for this period (n=19). The definition and optimization of temporal groupings prior to LDA deserves considerable further investigation using a variety of statistical methods, commonly categorized as “cluster analysis” tools. This kind of probabilistic approach to the data, if well executed, seems to have great potential for making sense of a very complex multidimensional dataset, and for generating meaningful and prudent predictions regarding authenticity and origin.
Figure 13 Results of a linear discriminant analysis performed on the XRF results from the reproduction gilt bronze mounts from the van Risenburgh commode (65.DA.4) featured in Figure 4. The analysis was performed using the elemental composition of 536 securely dated French gilt bronze castings as references; the software was Stata using the commands “discrim lda” followed by “predict kpp” (using the kth nearest neighbour measure of distance).

Of course, LDA can be used to evaluate the probability that an analysed artifact belongs to any kind of group, not just chronological groups, assuming that a suitable set of reference data is available that adequately represents the group. Such reference data must contain enough data points to offer a statistically valid representation of the inherent variability within each group. If this non-trivial condition is met, there is no reason that LDA could not be used to probe the differences between objects – not just of different periods, but also of different regions or even foundries and artists. Naturally, there is no guarantee that clear differences between groups will exist, but techniques such as LDA offer the possibility of evaluating the structure of large datasets to find and quantify differences where they do exist.

**Future directions in alloy research**

In a book published in 2009, *The Fourth Paradigm: Data-intensive Scientific Discovery*, a wide variety of scientists and medical professionals contributed papers focused on the idea that the field of science is currently moving into a new historical period in which the dominant paradigm for advancement and discovery is based on data-intensive research or eScience (Hey, Tansley, and Tolle 2009). The editors present the argument, first expounded by Jim Gray of Microsoft Corporation, that in the past, science has moved through periods of empirical discovery (the last thousand years), theory-driven
discovery (the last few hundred years), and computational discovery (the last few decades), but now many fields are advancing into a mode in which large amounts of data are generated in the initial phases of research, and the correlation structure of the data is then probed for unpredicted relationships that subsequently drive the development and testing of theories to explain the patterns observed (Markoff 2009).

This trend toward eScience has emerged most visibly in “big data” fields such as genomics, environmental sciences and high-energy physics; however, the same movement can be seen occurring (albeit on a smaller scale) in fields such as art conservation science and technical art history where the availability and use of instrumental methods of analysis has been increasing dramatically in recent years.

In particular, and of direct relevance to the study of copper alloys, recent advances in the miniaturization of both X-ray tubes and X-ray detectors along with steep reductions in cost have meant that the use of XRF instrumentation in art and archaeology has exploded in the last several years. It is probably not an exaggeration to say that more art- and archaeology-related XRF spectra have been generated in the last five years than were generated in the previous 85 years, since X-ray spectroscopy became an established technique around 1920 (this is, admittedly speculation, but seems likely, especially given the rapidly expanding use of XRF scanning in which thousands, or tens of thousands of spectra are routinely generated and combined to produce images based on elemental composition). This means that the generation of datasets such as the compositional database for French gilt bronzes discussed here is within the realm of possibility for an ever-increasing number of institutions and individuals worldwide.

In principle this augurs the beginning of a golden age for elemental analysis of copper alloy artefacts such as gilt bronze and bronze sculpture. As the body of securely validated compositional data grows, temporally, geographically and typologically, the ability to analyse the data in sophisticated ways and make new insights should grow correspondingly. However, there are some serious obstacles to be overcome before the promise can become reality.

One of the important points associated with the idea of eScience is that it depends fundamentally on large, well-coordinated international teams of collaborating scientists and researchers to produce, share and archive large amounts of data. An obvious corollary to this point is that the shared data must be produced by valid methods and be comparable and reproducible between collaborators. Unfortunately, the reproducibility of quantitative XRF results between laboratories, particularly for copper alloys, is difficult to ensure. A recent interlaboratory reproducibility study has demonstrated that quantitative alloy analysis by XRF, as currently practised in many museums and university laboratories active in the study of copper artefacts, is not sufficiently reproducible to be useful for collaborative research (Heginbotham et al. 2011). There are probably several reasons for this (a topic beyond the scope of this paper) but for the time being, the fact of poor reproducibility severely limits the pursuit of statistically rigorous studies, utilizing compositional data acquired from multiple international institutions. Without the large and reliable datasets that such collaborative studies could provide,
elemental alloy analysis will never achieve its potential to provide fundamentally new insights.

Fortunately, some progress toward interlaboratory reproducibility is already being made and the prospects for continued improvement seem promising. Already an informal international consortium of eight museums and universities has come together to specify and commission the production of a new set of 14 certified reference materials (CRMs) tailored to historic copper alloy analysis by XRF (Heginbotham et al. 2015). The complete set is now available to museum and arts-oriented laboratories anywhere in the world for purchase at a discounted rate. Common use of this standard set should go a long way towards improving interlaboratory reproducibility, and plans are afoot for a new international study to measure the anticipated improvement. Additional advances in reproducibility should also come from ongoing improvements in spectral interpretation software, a factor that has been shown to be critical for obtaining highly reproducible results (Heginbotham et al. 2011).

Another challenge that needs to be addressed in order to achieve success with an eScience approach to elemental analysis is the development of an effective, shared information management structure. The community of scientists and conservators interested in the composition of historic copper alloys will have to organize and maintain the large amounts of data and metadata that will be generated, ensuring both the quality and accessibility of the data. Ideally, this will lead towards a large shared database, with a commonly agreed upon field structure and a format that will allow the maximum possible versatility in data analysis and visualization. And, of course, the collaborators in this research will need to have the opportunity to learn how to effectively contribute to and utilize the research network as it develops.

All of these ideas regarding future directions for alloy research represent ambitious, long-term goals. There is however reason for optimism, and with steady work and commitment, the emergence of a strong and truly collaborative research programme seems entirely within reach.

Conclusions

The technical examination of gilt bronze is, and should be, a multidisciplinary affair. An informed assessment of the technical characteristics of an object should never be made simply on the results of one method of examination. Rather every effort should be made to use a variety of techniques and base conclusions upon the preponderance of the evidence provided by all the available methods. Visual examination of both finished and unfinished surfaces is a critical part of any technical study and success in this pursuit relies heavily on experience and focused attention to detail. X-radiography may not always be necessary, but can certainly offer important insights, particularly regarding the intricacies of the casting technique for figural lost wax cast elements. There is also untapped potential for X-radiographic methods to be used for dating and provenancing
through metrological studies of fasteners and tool marks. Finally, it is becoming ever clearer that elemental analysis and the study of alloy compositions can make an important contribution to the study of gilt bronze objects and to copper alloy artefacts in general. The use of XRF for quantitative analysis has great potential to answer previously unanswerable questions about origin, attribution and authenticity. This promise will be most likely to be realized if a rigorous eScience approach is followed, characterized by well-coordinated international collaboration in data acquisition, effective information management strategies, and a sophisticated approach to statistical evaluation of the data.

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