number: "I.2"

title: Metals

subtitle:

contributor:

* first\_name: David

last\_name: Bourgarit

bio: David Bourgarit (Archaeometallurgist, Centre de Recherche et de Restauration des Musées de France [C2RMF], Paris, and Laboratory TEMPS-CNRS-Nanterre University) has a background in physics, with a PhD on the physical metallurgy of a specific titanium alloy. Since 1996 he has been a researcher at the C2RMF, where he has been investigating metallic artifacts from almost all periods and regions. His primary research interests are in the technological approach to copper metallurgy, with a focus on the provenance of copper and fabrication techniques. He coedited *French Bronze Sculpture: Materials and Techniques 16th–18th Century* (2014).

additional contributors: Aurélia Azéma, Ann Boulton, Joachim Kreutner, Andrew Lacey, Kenneth Lapatin, Elisabeth Lebon, Carol Mattusch, Benoît Mille, David J. Reid, David Scott, Donna Strahan, Jean-Marie Welter

abstract: This chapter overviews the composition and properties of the copper alloys used to make cast sculptures and sculptural objects, and presents the reasons why it might be helpful to identify them as part of the technological investigation of a bronze sculpture. The text aims to explain and unravel common approaches to the varied nomenclature applied to such alloys, and introduces two main parameters by which metals can be characterized: their chemical elemental composition and their microstructure. These two parameters control an alloy’s chemical properties and physical properties. The reasons why and how an alloy’s microstructure, metallography, phase diagrams, and so on can contribute to a technological study are outlined.

short\_title: Metals

This chapter overviews the composition and properties of the copper alloys used to make cast sculptures and sculptural objects, and presents the reasons why it might be helpful to identify them as part of the technological investigation of a %%bronze%% sculpture. The text aims to explain and unravel common approaches to the varied nomenclature applied to such alloys, and introduces two main parameters by which metals can be characterized: their chemical elemental composition and their microstructure. These two parameters control an alloy’s chemical properties (for example its %%corrosion%% resistance) and physical properties (for example its color and strength). The reasons why and how an alloy’s microstructure, metallography, phase diagrams, and so on can contribute to a technological study will be outlined. The more complex discussions will be most relevant to those who are directly involved in the technical analysis of bronzes. Recommendations for determining metal composition are set out in [II.5](#II.5).

## 1 What is bronze?

The term “bronze” has various meanings. It may designate a copper alloy that has tin as the primary added element, or any other copper-based alloy. In fact, in common parlance, “bronze” is used to describe most copper alloy sculptures regardless of the actual elemental composition of the alloy. Either inherently or by design, bronze sculptures generally include a number of other elements, but we recommend reserving the term specifically for copper-tin alloys, as will be explained.

### 1.1 Why create an alloy?

Adding different metallic elements to copper makes it possible to control the resulting alloy’s properties (for instance %%castability%%, strength, resistance to corrosion, workability) as desired by the sculptor or %%founder%% (see **table 6**, also [I.2§2](#I.2§2) below). Cultural influences, the cost of raw materials, the desired color, and/or the need for the %%cast%% to take %%gilding%% may also play a role in the choice of alloy. Historically, except for %%brass%%, copper alloys were produced by combining the different metals in a crucible or furnace at the time of the %%pour%%.[[1]](#endnote-1) Increasingly, commercial art foundries have tended to acquire pre-alloyed ingots.

### 1.2 Elemental composition of metals

Elemental composition should be distinguished from both structural composition (see [II.6§2.1](#II.6§2.1)) and isotopic composition (see [II.5§5](#II.5§5)). Most metals occur in nature as ores in a mineral form, and are extracted from the earth. Even when refined, the extracted metal is rarely 100 percent pure; other elements will be present in small amounts as impurities, described as the “impurity pattern.” The elements are set out in the periodic table, where each is given a symbol (**table 7**, **fig. 131**)—for example, Cu for copper, Sn for tin—so that scientists can quickly discern its properties. Analysis of any historic or contemporary bronze sculpture will likely reveal a variety of elements even within a simple alloy. In addition to the impurities or trace elements present within each metal, other elements may have been deliberately added for practical or aesthetic reasons.[[2]](#endnote-2) There is also the common practice—even today—of adding metal that has been previously used, for instance the %%sprues%% and casting cups cut off of previous casts.

### 1.3 Alloy nomenclature

#### 1.3.1 Different users, different nomenclatures

“Bronze” has become a generic term to describe sculpture that may in reality have been made from a large variety of copper alloys, from non-alloyed copper to high-zinc brasses as well as ternary and quaternary alloys (those made up of primarily three or four elements, respectively). The usage and understanding of alloy nomenclature varies considerably across historical sources, as used by craftspeople and modern industry and/or by those studying bronze sculpture.[[3]](#endnote-3) The complexity and lack of uniformity of terminology in modern industry alone exemplifies the situation.[[4]](#endnote-4) Technical studies of large groups of related copper-based items tend to show that alloys and their uses evolve greatly over time and place, and thus our nomenclatures for them varies accordingly.[[5]](#endnote-5)

The discrepancies are partly related to varying viewpoints on the percentage at which an element present in the metal (lead, tin, zinc, arsenic, et cetera) should be considered an alloying element (intentionally added or kept in the metal) or an impurity (unintentional). The still-loose understanding of the effect of the different elements on the properties of alloys is partly responsible for the lack of clarity.[[6]](#endnote-6)

#### 1.3.2 Pragmatism should be the rule

The present *Guidelines* do not aim to impose any norm and cannot address all issues, but the following are some parameters:

* “Bronze” is used extensively in this volume, and continues to be the preferred term for many artistic objects or sculptures %%cast%% from copper alloys regardless of their actual composition, even if they are known to be technically different (for example brass) or more nuanced (for example leaded bronze, quaternary alloy).
* When writing a report or publication it is important to detail the results of analysis (if any) and identify which alloy definition (if any) will be used, either referring to existing formulas or defining new ones.[[7]](#endnote-7)
* The alloy nomenclature compiled by scholars for the present *Guidelines* is intended as a useful starting point (see **table 8**).
* The terms “major,” “minor,” and “trace” in reference to elements do not convey any judgment regarding whether an element is present intentionally or not, unlike the terms “alloying elements” and “impurities.” As such, these terms might be a good compromise. Symbolic thresholds are often put forward in both industry and cultural heritage fields to define these three terms:
* 1wt% (1 percent of the total weight) is considered a major element, and so copper containing 1wt% lead is a leaded copper.
* Under 1% means the lead (or any other element) is considered a minor element.
* Under 0.01% (100 ppm), the lead is considered a trace element.[[8]](#endnote-8)

### 1.4 Chemical symbols and formulas

Scientists generally use the chemical formula to describe the known alloy content (for example, after analysis). Using a chemical formula to describe an alloy could avoid misunderstandings, although even then, various nomenclatures coexist, and nonscientists may not be familiar with chemical symbols (**table 7**). For a generic designation, Cu-Sn can be used for copper-tin alloys, Cu-Zn for brasses, Cu-Sn-Zn for ternary alloys, and so on. For semi-quantitative compositions, the ECS (European Committee for Standardization) and ISO (International Standardization Organization) norms are often used, for example CuZn7Sn3Pb2 when the number refers to the rounded %wt. Note that only whole numbers are reported, which means that any chemical element in an amount lower than 0.5wt% is not represented.

## 2 What are the main physical and chemical properties of copper alloys?

Leaving aside the impact that cultural influences and availability of raw materials may have on the choice of alloy, key considerations will be its melting temperature, castability, hardness, %%weldability%%, and suitability for %%patination%% and/or %%metal plating%%. Other properties that may be factored in are linked to the function and life cycle of the statue, such as its color, shine, strength, and symbolic properties.[[9]](#endnote-9) These properties may vary greatly across different copper alloys.[[10]](#endnote-10) While the influence of the composition on copper alloy properties is far from being fully characterized, especially for historical alloys, it is worth attempting to describe the role of the alloying elements in a qualitative rather than quantitative manner in the following sections and in **table 6**.[[11]](#endnote-11)

### 2.1 Melting temperature

The melting temperature of copper alloys varies from 1084°C (pure copper) to approximately 1000°C for a copper bearing 10wt% tin (**fig. 132**) or 20wt% zinc, and down to 955°C for a highly leaded copper (36% lead). Melting temperatures as low as 900°C can be reached, for example, with 20wt% tin or 40wt% zinc. These temperatures hold for “normal” pressure conditions, namely 1 bar. Low melting temperatures are a distinct advantage for casting, as long as the other desired properties are not compromised.

### 2.2 Castability

The castability of a metal or alloy is best defined as its ability to fill in and pick up every detail of a %%mold%%. The castability will be affected by two main parameters, namely the metal properties and the mold characteristics, and of course the pouring temperature. Numerous metal properties, mainly controlled by the alloy composition, impact the castability. As an example, because unalloyed copper easily oxidizes, it is difficult to cast.[[12]](#endnote-12) Conversely, lead is known to greatly enhance castability.[[13]](#endnote-13)

### 2.3 Color

While all metals are opaque, and more or less shiny when polished, only gold and copper are not white or whitish. The color palette of copper and its alloys depends primarily on the alloy composition (see **table** **6**).[[14]](#endnote-14) The addition of zinc to copper has a particularly pronounced impact on its color, lending it a gold-like appearance (**fig. 133**). The addition of silicon or aluminum yields similar colors. The visual differences between tin bronzes with different tin contents are not necessarily marked (**fig. 134**), unless high quantities (more than 15wt% of tin) are added, such as those used for mirrors and bells.

The color palette of copper and its alloys, and their visual appearance more generally, depends also on the surface texture. For this reason, and because metals are glossy, determining how to characterize or describe the color of copper alloys is quite complex, not to mention the various alterations of the surface, including the patina (for more on color measurement, see [II.2§4](#II.2§4)).

### 2.4 Hardness: cold working and/or machinability, wear resistance

Cold working includes %%fettling%%, %%chiseling%%, %%chasing%%, and polishing (see [I.6§1.2](#I.6§1.2)). Cutting and compressing are the main actions involved. The principal related material property is hardness, and what modern metal handbooks report as “machinability” (the ease with which a material can be formed with a cutting tool).[[15]](#endnote-15) The hardness of a metal depends greatly on its composition (see **table 9**). As will be seen below, microstructure also greatly impacts hardness, but by definition cast bronzes are mainly in an as-cast state, and thus do not generally show large variations in microstructure. Soft metals such as unalloyed copper are particularly difficult to cut; they tend to smear under a cutting tool or during polishing. For hard metals, such as 10% tin bronzes, a small addition of lead improves machinability.[[16]](#endnote-16) Several standardized tests are available to measure hardness; sampling is usually necessary.[[17]](#endnote-17)

### 2.5 Suitability for patination, gilding, and metal plating, and/or corrosion resistance

The chemical composition of an alloy controls its reactivity to chemical attack—in other words, what might be called its suitability for patination (see [I.8§1.1.1](#I.8§1.1.1)). This property is also directly linked to corrosion resistance.[[18]](#endnote-18) An alloy’s suitability for plating (for example gilding and tinning) depends on both the technique used and the metal. For example, tinning based on tin sweat can obviously only be performed on tin-bearing alloys (see [I.7§1.3.2](#I.7§1.3.2)). Also, leaded alloys are thought not to be adapted to fire gilding although this is not a universal rule (see [I.7§1.1.2](#I.7§1.1.2)).

### 2.6 Mechanical ductility and strength

Most common metals, and notably copper alloys, offer one remarkable property when compared to stone: they are ductile, as opposed to brittle. Metals can be heavily deformed before breaking. In addition, a number of copper alloys, including bronzes, have relatively high tensile strengths: much effort is needed to deform a bronze sword by stretching or bending (and even more so a statue).[[19]](#endnote-19) The direct consequence of these two properties—ductility and strength—is that bronze sculptures can support heavy loads, allowing artistic compositions of considerable freedom (**figs. 135, 136**). While a support is often integral to the composition of a stone or marble sculpture—such as a tree trunk attached to the legs of a standing figure, or a large strut beneath a rearing horse—the bronze equivalent will not require such a support.[[20]](#endnote-20)

A finished bronze sculpture is rarely supported by its internal %%armature%%, as its own metallic structure is sufficient. Hollow statues are even more resistant because of their tube-like shape; a tube is much harder to bend than a solid rod. A number of large sculptures, including Greek and Roman bronzes, demonstrate this, as the armatures (if they once existed) were usually removed before the separately cast sections were assembled (**figs. 137, 138**).

Other mechanical properties include elasticity, fracture toughness, and more, but these are of little interest in relation to most bronze sculptures.[[21]](#endnote-21)

### 2.7 Weldability

The ability of copper alloys to be assembled, particularly by welding, is an important consideration, as founders select metals for the cast and the weld. This must have been as true for metalsmiths using flow fusion welding during antiquity (see [I.5§1.1.1](#I.5§1.1.1), [Case Study 1](#CaseStudy1)) as it is for welders in modern-day foundries.

### 2.8 Symbolic properties

In certain cultures, metals, and notably copper alloys, have been (and still may be) imbued with specific spiritual powers. These may be attributed to the metal and ascribed to various intrinsic properties, such as color or smell.[[22]](#endnote-22) Rarer metals and other materials may also be added to the melt as part of a symbolic or spiritual ritual.[[23]](#endnote-23)

### 2.9 Is there an “ideal” copper alloy for bronze sculpture?

The variety of alloys encountered in bronze sculpture throughout history tends to show that there is no ideal alloy. There are a variety of reasons for this, starting with the potential competition between properties—including hardness and castability—depending on the requirements of the finished work. The destination of the sculpture and the way it is worked (amount of chiseling, nature of the patina, gilding, et cetera) are key, not to mention tradition and habits (see [Case Study 7](#CaseStudy7)).

However, very satisfying compromises may be found. Bronze with approximately 10% tin provides a good balance between castability, corrosion resistance, mechanical strength, and hardness. This alloy became a standard as early as the Late Bronze Age for tools and weapons,[[24]](#endnote-24) and for large bronzes during antiquity.[[25]](#endnote-25) That said, copper alloys containing zinc are also widespread, notably in modern times.[[26]](#endnote-26)

## 3 What is microstructure? What does it reveal about the making of a bronze? And how might it influence some of the alloy properties?

### 3.1 How can we distinguish whether a sculpture has been left as cast or has been cold worked, and why is this significant? Dendritic versus recrystallized microstructure

The atoms that make up a metal or an alloy align themselves in geometric patterns, as opposed to most glass types, whose atoms are distributed randomly. These patterns are cubes for copper and copper alloys (**fig. 139**), with various displays of the atoms depending on the composition of the alloy: these are the phases. These patterns in turn form specific structures called microstructures. Once in a while, one might encounter a fine textile- or branch-like pattern (**fig. 140**) or a geometrical one (**fig. 141**) within the surface of a bronze. This is the microstructure of the metal, and is not to be confused with the mineralized remains of organic materials (pseudomorphs) that may form upon contact with a bronze surface during prolonged burial.

As when studying the crystalline structure of a rock, a cross section with specific preparation is necessary to investigate the microstructure of a metal sample through metallography (see [I.2§5](#I.2§5) below; also [II.5§6](#II.5§6)). This structure can give clues as to whether the sculpture has been reworked or not, and potentially whether there are %%cast-on repairs%%. Two very different metallurgical states—and consequently microstructures—are found in cast bronze sculpture. The first corresponds to the as-cast state and exhibits a dendritic microstructure (**figs. 142, 143, 144, 145**). The second reflects disturbance of the dendritic structure by cold working, and sometimes by subsequent heating (metallurgists use the term “annealing”), in the areas closest to the worked surface. This may result in a recrystallized granular microstructure (**figs. 144, 146, 147, 148**). The microstructure affects physical and chemical properties dramatically, particularly corrosion resistance and mechanical properties. For this reason, for instance, hammered-in repair %%patches%% may stand out from the surrounding cast bronze setting because their crystallized microstructure oxidizes or otherwise patinates in a different way (**fig. 125**). The hardness of an as-cast bronze may be greatly increased by distorting the dendritic as-cast microstructure through hammering (see [I.6§3.3](#I.6§3.3)).

### 3.2 Primary versus secondary casting: welding, soldering, cast-on repairs

In addition to cold working, the metallic microstructure may record another type of technical process, namely the addition of a metal melted *onto* the primary cast. Such cast-on additions may occur as repairs (see [I.4§1.2](#I.4§1.2)) and/or assemblies such as %%brazing%%, welding, or %%soldering%%. However, the microstructure of the primary cast will only be impacted if the incoming metal is hot enough. This only occurs with welding.

### 3.3 Are metallographic investigations necessary?

Sampling for the purpose of metallographic study should only be considered in order to address very specific questions. Some assembly techniques and repairs may be advantageously investigated through metallography. Metallographic investigations have so far proven the only way to positively confirm the use or not of flow fusion welding and to characterize the degree of mastery involved (see [I.5§2.2](#I.5§2.2)). Similarly, in some instances only metallography can distinguish between cast-on and mechanical repairs (see [I.4§2.1](#I.4§2.1)).

Metallography also provides excellent evidence of the presence or absence of cold and/or hot working.[[27]](#endnote-27) Theoretically, it might also provide evidence of conditions during casting.[[28]](#endnote-28) Metallographic sampling is not readily done on relatively pristine works, especially since the areas that would be most interesting to sample tend to be on the outer surface, in clearly visible areas. Less invasive methods are available, but there are limitations to their ability to answer certain questions (see nondestructive testing in [II.2](#II.2)).

## 4 Why investigate metal composition and properties? and other FAQs

### 4.1 Why analyze the metal composition?

A number of questions may be addressed by investigating the metal composition. Alloy determination may be required for broad documentation—defining whether a sculpture is bronze or brass, for instance. Some specific alloys may be associated with specific periods, production centers, or workshops, and/or may refer to specific constraints (technical, economic, political, cultural).[[29]](#endnote-29) Impurity patterns in the metal may help to group statues or fragments of statues (in conjunction with other data),[[30]](#endnote-30) tackle the provenance of the raw metal,[[31]](#endnote-31) and/or detect particular applications and processes.[[32]](#endnote-32) See **table 10** and [II.5§1](#II.5§1) for a discussion about limitations.

### 4.2 Can metal composition help to authenticate a bronze sculpture?

Both alloy composition and impurity patterns may be used for authentication,[[33]](#endnote-33) although the ubiquity of compositions in both space and time often renders the task complex.[[34]](#endnote-34) A combination of technical markers and archaeological and/or historical information is often necessary.

### 4.3 Can metal recycling be detected analytically?

There are no specific characteristics of metal composition useful for definitively distinguishing fresh metal from recycled. One way to detect the probable occurrence of metal recycling is to investigate the evolution of metal composition within a large group of well-contextualized bronzes. This has been tested for archaeological bronze artifacts, since some chemical elements such as arsenic are volatile, and their content may slowly decrease with repeated recycling (remelting).[[35]](#endnote-35) But the authors do not know of any such studies on bronze sculpture. Archives such as commission contracts sometimes specify that scrap metal should be used, or, conversely, that it should not be used (although such documents cannot be blindly trusted as reliable).[[36]](#endnote-36)

### 4.4 Is it useful to know the physical and chemical properties of the metal in a sculpture?

Leaving aside conservation issues, there are a good number of reasons to want to understand the properties of the metal, for all the aforementioned points ([I.2§2](#I.2§2) above) and more. Knowing a given property may add to the discussion of the intentionality of the presence and/or the amount of a given element, and the objective targeted by the commissioner, the artist, and/or the founder. For example, one may be able to discuss the presence of high amounts of lead in a given sculpture: If intentional, was it to enhance castability, to lower the cost of the metal, or because of tradition or beliefs? This may then open up large avenues for research (transfer of know-how and knowledge, trade in materials, et cetera).

## Notes

1. In Europe, brass was once made by so-called cementation, a relatively complex process where metallic copper was mixed with zinc ore. The use of metallic zinc to create brass was not mastered until the mid-nineteenth century (see {Bourgarit and Thomas 2015}). [↑](#endnote-ref-1)
2. {Young and Pernicka 1999}. [↑](#endnote-ref-2)
3. See {Motture 2019}, 18–21 for a brief summary of medieval and Renaissance terminology and issues around the different interpretation of early sources, including the interchangeability of the use of *aes* (bronze) and *aurichalcum* (brass, but literally “golden copper”). See also {Welter 2018} and {Thomas 2009}, 498–510. The nomenclature of copper alloys is an old issue among scholars (see {Rickard 1932}). [↑](#endnote-ref-3)
4. For example, in modern industry, the term “red brass” designates two very different alloys depending on its use. For wrought alloys, red brass is a binary alloy, typically CuZn12-15, sometimes called tombak. For cast alloys it is a quaternary alloy, typically CuSn5Zn5Pb5. [↑](#endnote-ref-4)
5. For example, two different sets of nomenclatures have been proposed for medieval common metalware found in London ({Bayley 1991}) and in Paris ({Bourgarit and Thomas 2012}). Note that in both cases, compositions with up to 2–3 wt% of zinc, tin, and lead are still considered unalloyed copper. [↑](#endnote-ref-5)
6. For cultural heritage copper alloys, some answers are given in {Young and Pernicka 1999}. See also {Welter 2007}. [↑](#endnote-ref-6)
7. Nomenclatures published to date for historic coppers are mainly related to medieval and modern European contexts ({Bayley 1991}; {Glinsman and Hayek 1993}; {Motture and Martin 2001}; {Bourgarit and Thomas 2012}). Modern standards can be used as well (ASM, AFNOR, et cetera), although they may not be as appropriate for historic alloys. For example, for the ASM, 2.5% lead would be a so-called extra-high leaded alloy, whereas in ancient Greek and Roman sculptures such alloys would be characterized as unleaded (high-leaded bronzes bear up to 30% lead in Roman statues). Similarly, a 10% zinc alloy is called a commercial bronze. Although terms such as “leaded bronze” or “brass” are used, they should always be followed by a summary of the alloy by percentage if available. [↑](#endnote-ref-7)
8. An interesting definition of “minor element” has been proposed ({Welter 2007}, 95): “Elements which by amount range between the intentionally added major elements to adjust the properties of copper and the unavoidable trace elements which are basically considered as a nuisance.” However, these guidelines are not standard, and not always adhered to in the art historical literature, for example. [↑](#endnote-ref-8)
9. There are a plethora of references on this subject; see for example {Stewart 2014}; {Motture 2019}. [↑](#endnote-ref-9)
10. {Cottrell 1967}, 39 neatly explains that all these properties specific to metals (when compared to other materials such as stone or ceramic) are due to the “pervasive glue” stemming from the specific metallic bond between atoms. See also {Smith 1981}. [↑](#endnote-ref-10)
11. Metal handbooks provide the most comprehensive synthesis for industrial alloys; see for example {Davis 1998}. [↑](#endnote-ref-11)
12. However, unalloyed copper sculptures of various sizes and from diverse cultures were successfully cast, as for example an anthropomorphic solid figure dated from the early second millennium BCE, India, H. 45cm (Musée des Arts Asiatiques de Nice, inv. 2002.2.1, see C2RMF internal report #3086, 2002), some of the Tibetan statuettes from the seventeenth and eighteenth century in the British Museum collections ({Craddock 1981}), and the large sixteenth-century Wolsey Angels in the Victoria and Albert Museum (V&A A.1 to A.4-2015; h. between 101 and 108 cm each; see {Motture 2019}, 197–98 with additional references) (as yet unpublished analysis undertaken by the author as part of the collaborative V&A Wolsey Angels Research Project; forthcoming ca. 2022). [↑](#endnote-ref-12)
13. A comprehensive description of which metal and mold properties control castability is beyond the scope of the present guidelines; please refer to the specialized literature ({Lesoult 1986}; {Beeley 2001}, 17–25; {Campbell 2003}, 75–95). A very clear synthesis has been proposed by {Mille 2017}, 378–404, including the role of lead in castability of protohistoric and historic copper alloys. This latter topic has been long debated among archaeometallurgists. A recent experimental development ({Mille 2017}) has demonstrated, for the first time, the influence of high lead content (above 10wt%) on the castability of copper alloys under specific conditions (mold made of low thermal diffusivity material such as clay or plaster, preheated mold). [↑](#endnote-ref-13)
14. For ancient copper, see {Mödlinger et al. 2017}. For the most recent measurement attempts and an updated bibliography, see {Radivojević et al. 2018}. [↑](#endnote-ref-14)
15. According to US standards, machinability is scaled against the most machinable alloy, namely the “free-cutting brass C3600” (35.5% Zn, 3% Pb) for copper-based alloys; see {Tyler and Black 1992}, 760. Hardness is reported either quantitatively ({Tyler and Black 1992}, 779) or qualitatively according to the metallurgical state, annealed, et cetera (hard, 1/2 hard, 1/4 hard, etc.); see {Tyler and Black 1992}, 817. [↑](#endnote-ref-15)
16. This was notably clear on the Greek Vix crater (Châtillon-sur-Seine, France, sixth century BCE, one of the largest bronze vessels known in antiquity). It was shown that around 1wt% lead had been deliberately added to the 10% tin bronze to facilitate %%engraving%% of the cast elements of the frieze and handles ({Mille and Bourgarit 2003}). [↑](#endnote-ref-16)
17. {Revankar 2000}; {François 2004}. [↑](#endnote-ref-17)
18. It is beyond the scope of this essay to discuss when, where, and how founders paid attention to the alloy composition with respect to patination. [↑](#endnote-ref-18)
19. Most weapons and tools were made of bronze during the Middle Bronze Age and Late Bronze Age. [↑](#endnote-ref-19)
20. Actually this is a complex matter, and the presence (or not) of struts is now understood as not simply a question of bronze versus marble, notably for Greek and Roman sculpture. Bronzes can have struts too, although it is not clear why (see for example the statue of a young Dionysos from the Chicago Art Institute, published in {Mattusch 1996}, no. 23, 224–31. And marbles can have them or not (see {Hollinshead 2002}; {Anguisola 2018}), as kindly indicated by Carol Mattush, June 2019. And it is not clear whether all marbles really need the struts that appear; in some instances they may be due to workshop practice ({Anguisola 2018}). [↑](#endnote-ref-20)
21. For more on mechanical properties of cast metals, see {Campbell 2015}, chapter 9. [↑](#endnote-ref-21)
22. See the “red gold” in Africa ({Herbert 1984}); the evil properties of copper in the pre-Hispanic Caribbean ({Martinón-Torres et al. 2007}); the cosmological and gender connotations of copper in Colombia due to color and smell ({Falchetti 2003}); and the curative properties of the Khmer *samrit* ({Vincent 2012}, 297–301). See also {Stewart 2014} for ancient Greece; {Motture 2019}, esp. 15–17 for Renaissance; and {Droth et al. 2005} generally. [↑](#endnote-ref-22)
23. Gold and jewelry are added in the melt for Buddhist statues today. The metal of church bells is still blessed before casting in various countries, including France (see <http://www.youtube.com/watch?v=5gg3THv4vfI>, thanks to Alice Chéron, Ecole du Louvre). Also still common today is the practice of adding remelted metal that has been previously used, as recommended for example by Pliny the Elder for its “seasoned brilliance . . . tamed by perpetual use” ({Pliny the Elder 1857}, 34.20, p. 199) and by Pomponius Gauricus (Italian, 1482–1530): {Gauricus [1504] 1886}, 222–23; {Gauricus [1504] 1969}, 218–19; {Gaurico [1504] 1999}, 228–29. [↑](#endnote-ref-23)
24. {Pernot 2000}. [↑](#endnote-ref-24)
25. {Mille 2012}; {Mille 2017}; {Descamps-Lequime and Mille 2017}. Zinc is detrimental to welding, and since welding was systematically carried out on ancient large bronzes, the works never contain more than 1% zinc. [↑](#endnote-ref-25)
26. Although related to decorative arts gilt bronzes rather than statuary, an innovative study carried out by French chemist Jean-Pierre-Joseph d’Arcet (published in 1812) to determine which brass would meet most technical requirements is of interest in this context. Eight alloys were tested by craftspeople involved in the production, namely founders, %%chasers%%, turners, and gilders. Only one was rated very good, which happens to be very similar to the alloy found in eighteenth- and nineteenth-century French gilt bronze ({Heginbotham 2014}). [↑](#endnote-ref-26)
27. The authors do not know of such investigations on bronze sculpture but are aware of some on other types of prehistoric and historic bronzes (see notably {Chase 1994}; {Pernot 2000}; {Scott 2014}). [↑](#endnote-ref-27)
28. The investigation of the microstructure (such as grain size, the interdendrite spacing, and the composition of the various phases, see [I.2§3](#I.2§3) in the present chapter), may provide a lot of information about the casting conditions (pouring temperature, mold materials, and so on). Yet given the number of parameters potentially controlling the microstructure, the task of distinguishing which parameters are responsible for the observed microstructure is very complex. Given the invasive aspect of metallography, it is understandable that no such study has been carried out on bronze sculpture. [↑](#endnote-ref-28)
29. See [Case Study 5](#CaseStudy5) and a number of other studies on ancient large bronzes ({Mille 2012}; {Mille 2017}; {Descamps-Lequime and Mille 2017}); Khmer bronzes ({Vincent, Bourgarit, and Jett 2012}); and Venetian sixteenth- to seventeenth-century bronzes ({Motture 2003b}). For composition of Renaissance bronzes see for example ({Motture 2019}, 22–25). [↑](#endnote-ref-29)
30. Numerous examples are available for a variety of periods: {Bouquillon et al. 2006}; {Azéma et al. 2012}; {Vincent, Bourgarit, and Jett 2012}; {CAST:ING 2018}. See also Case Study 1 and Case Study 5. Note that in all cases, elemental composition alone was not sufficient to ascertain the grouping; other analysis (%%core%%) and/or approaches (style, archaeology) proved necessary. [↑](#endnote-ref-30)
31. {Bourgarit and Mille 2014}. [↑](#endnote-ref-31)
32. For example, the presence of phosphorous in the welding metal on the monumental Roman bronze foot from Clermont-Ferrand (**fig. 68**) has revealed the use of flux ({Darblade-Audoin and Tavoso 2008}). [↑](#endnote-ref-32)
33. For example, an alloy containing zinc can hardly be dated to an Angkorian production or found in a large antique bronze. And silicon bronzes and additions of phosphorous did not appear until the mid-twentieth century. [↑](#endnote-ref-33)
34. The same bronze composition may be found in a Javanese ninth-century statuette and a French sixteenth-century large bronze (see [Case Study 3](#CaseStudy3), [Case Study 5](#CaseStudy5)). [↑](#endnote-ref-34)
35. For example {Bray et al. 2015}. [↑](#endnote-ref-35)
36. See for example {Welter 2014}. [↑](#endnote-ref-36)