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| --- | --- | --- |
| **New #** | **Old #** | Caption |
|  | **480** | Diagram of generations of casts (here through the lost-wax process): a) the original model here is in clay, but could be made of any material; b) the translation of the original model into a wax inter-model may involve more than simple molding; c) a close reproduction of the original model will be referred to as a replica (a wax inter-model that is altered in details and with additional features [e.g., a base] will result in a %%variant%%); d) more alterations can be made after casting (e.g., with a base or a different patina); e) a bronze can in turn serve as model for another generation of casts by taking a mold of it; f) because wax shrinks as it cools, the inter-models are slightly smaller than the bronze model and their details softer unless reworked; g) the bronze after-cast may be in turn be reworked and finished differently than its original bronze model or sister casts. |
|  | **1095** | An internal core support is pushed into the plaster-based core of the wax leg as part of the experimental reconstruction of Mars by Andrew Lacey (British, b. 1969), 1997, after a model by Giambologna (Netherlandish, 1524–1608), ca. 1587, probably cast later, H. 40.7 cm (Victoria and Albert Museum, bequeathed by Dr W. L. Hildburgh FSA, inv. A.99-1956). See {Bewer 1996a}. |
|  | **1063** | Graph showing the impact of a lost-wax sculpture’s size on the time needed for the different steps in the fabrication process. The data is based on records gathered between 1973 and 2006 kindly provided by Jean Dubos, director of Fonderie de Coubertin, and are based on the casting of a standing nude man, whatever the model. The duration is given in person-hours and only factors in working hours; the time needed for drying and baking of the investment, for instance, is not taken into account here, although those steps can take a long time (as shown in **table 1**). Also, the more people working simultaneously on a bronze, the quicker the completion (again see **table 1**). |
|  | **485** | In-process detail of the first reconstruction by Andrew Lacey (British, b. 1969) of one of the so-called Rothschild Bronzes, attributed to Michelangelo (Italian, 1475–1564), H. 91.2 cm (private collection). The fresh casting has just been broken free from its investment. Note the marked granular texture of the bronze surface and the white plaster investment heavily bonded to it. See {Lacey 2018}. |
|  | **490** | In-process detail of the second reconstruction by Andrew Lacey (British, b. 1969) of one of the so-called Rothschild Bronzes, attributed to Michelangelo (Italian, 1475–1564), H. 91.2 cm (private collection). The casting has just been broken out of the mold with dark fire-skin and some of the investment bonded to the surface. Great care in the application of the first investment layers on the wax model resulted in a cleaner as-cast surface with little or no granular texture and minimal investment bonded to the surface, necessitating minimal chasing. See {Lacey 2018}. |
|  | **113** | Experimental sand-cast torso (H. 16 cm). Yellow overlay indicates the hollow lantern made of rolled sheet metal that runs vertically through the body and has been used to mount the torso to a base. See also the area where the bronze did not fill the mold, an extreme example of a cold shut. White arrows indicate the typically rounded edge of the bronze wall where it stopped flowing. Green arrows denote the seam line along the proper right side of the torso where bronze flowed into a gap along the joint of the cope and drag. Red arrows indicate flashing at either side of the lower horizontal armature rod. Made with consultant Tonny Beentjes, Decorative Arts and Sculpture Conservation, J. Paul Getty Museum. |
|  | **790** | Pouring layers of ceramic shell slurry onto the sprued wax of the horse’s head. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **582** | View of the inside cavity showing remnants of the casting core composed by pre-baked bricks (see overlay) and clayey refractory material. See also the two iron armatures (image width ~50 cm). Barthélemy Prieur (French, ca. 1536–1611), Peace, cast in 1571 by Nicolas Péron, H. 128 cm (Musée du Louvre, inv. MR1683). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}; {Castelle et al. 2021}. |
|  | **779** | Diagram depicting a version of the main steps in sand casting: 1) a chef-modèle or pattern is a specially designed model for sand casting made of a hard material—often metal—to withstand the repeated handling and ramming of sand within a multipart, stacked metal or wooden frame called a casting flask; 2) the pattern is buried about halfway in backing sand in a first section of the flask called the cope; piece mold sections are built up over the model with carefully rammed special casting sand that contains a binder to help the compacted sand hold the desired shape; 3) once the exposed part of the pattern is covered with mold pieces, the second section of the flask, or “drag,” is affixed to the cope and the piece-molded side is back filled with carefully rammed sand; 4) the tightly packed flask is flipped; the cope and backing sand, now on top, are removed to provide access for a similar piece-molding process to be performed on the other side of the chef-modèle; 5) the two-part casting flask is parted and the mold pieces carefully disassembled to remove the pattern; 6) to make a hollow cast, a core must be created to define the thickness of the bronze walls; this is made by ramming the same special casting sand into the hollow impression left by the chef-modèle; metal core supports (the crossed features in black) extending out into the surrounding mold pieces are incorporated into the new sand; the cope and drag are joined, thereby creating a sand replica; 7) the flask is opened again and the sand replica is removed and shaved down evenly overall to form the core; white areas indicate hollow spaces for metal to fill; the thin legs in this case will be solid, and so will not need a core (in [Case Study 6](#CaseStudy6), the core supports were metal tubes that served as core vents as well); 8) the sand mold and core are baked, then carefully reassembled in the cope and drag; the core supports projecting from the core serve to suspend the core in place; channels are cut strategically into the mold to ensure the efficient distribution and flow of the metal and venting of air; 9) the cope and drag are reassembled and locked together, and the metal alloy, which has in the meantime been liquefied, is poured into the mold; 10) once the metal has solidified and cooled, the sand mold is broken open and the bronze cast removed; the metal sprues that have formed in the channels are cut off; and the surface is cleaned and repaired as needed; 11) the bronze surface may be reﬁnished with details before joining the separately cast arms and base. As a final step, a patina may be applied. Diagram based on Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). See [Case Study 6](#CaseStudy6). |
|  | **831** | Large casting flaws in the arms of a Khmer divinity reveal the tan-colored, clay-based core that remains inside the bronze. Note the very thin walls of the bronze at the edges of the losses. Standing Buddha in Abhayamudrā, post-Angkorian, Prasat Bakan (Pursat), 16th century, H. 24.2 cm (National Museum of Cambodia, inv. Ga.3330). |
|  | **780** | Diagram depicting an example of life-casting: 1) the lizard is placed in a bed of clay; rolls of wax are strategically joined to the lizard to form the sprue system; a clay wall is then built around it; 2) a plaster-based slurry is poured over the lizard and sprue system, embedding the lizard and sprues, forming the top half of the refractory mold; 3) when set, the mold is turned over, the bottom clay slab is removed, and new clay walls are built up to contain the other half of the mold and additional refractory material is poured in; 4) the mold is heated until dry; the wax and as much of the lizard as possible are burned away; the bone remnants can be removed by opening the mold; 5) the two sides of the mold are clamped together and filled with molten bronze; 6) the refractory mold and sprue system are removed from the cast; 7) the finishing of the solid bronze includes sharpening of details as needed and patination. Diagram based on research related to the Making and Knowing Project at Columbia University. See {Lacey and Lewis 2020}. |
|  | **897** | Overall view and X-ray radiograph of the earliest known object made by lost-wax casting. Copper Amulet, Mehrgarh, Baluchistan, mid-5th–mid-4th millennium BCE, diameter 2 cm (Mission Archéologique Française du Bassin de l’Indus, inv. MR.85.03.00.01). See {Thoury et al. 2016}; {Mille 2017}. |
|  | **579** | Diagram depicting a version of the direct lost-wax casting technique: 1) an armature is constructed of iron rods and wires; 2) a refractory clay investment is built up over the armature to form the core; 3) a wax layer is then modeled over the core and details refined in order to create a unique wax model; 4) the wax sprue system is joined to the model and core pins inserted through the wax and into the core; 5) the wax is invested in a refractory mold; 6) the mold is heated until dry and all traces of wax are melted and burned out; 7) the mold is filled with molten bronze; 8) when the metal is cool, the investment, core pins, and sprue system are removed; 9) chasing includes polishing, burnishing, and the addition of texture and sharpening of details as needed. As a final step, the surface is patinated. Diagram based on X-radiographs of Adriaen de Vries (Netherlandish, 1556–1626), Juggling Man, ca. 1615, H. 76.8 cm (J. Paul Getty Museum, inv. 90.SB.44). See **fig. 79**, {Bewer 1999}. |
|  | **163** | Detail of an Eben ceremonial sword on the back of a pendant, possibly a maker’s mark. Pendant with Royal Triad, Benin kingdom, Nigeria, 18th century, H. 15.4 cm (Weltmuseum Wien, Vienna, inv. VO 64271). At least twenty pendants are known to bear this mark on their backs. |
|  | **924** | Plaster molding of the 3D resin print of the head of Apollo of Lillebonne during the 2016 CAST:ING meeting, Coubertin foundry, France. Top left: plasticine (black) is used to mark the sections of the piece mold on the resin head (yellow). Top middle and right: plaster is applied to the model in sections. Bottom left: the completed piece mold. Bottom middle: the separate sections of the mold are separated. Wax or clay will be applied on the internal surface by different methods (slabs, painting, balls, see **figs. 17, 19, 24**). Bottom right: the reassembled piece mold is used for slush molding. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **785** | Diagram depicting a version of the lost-wax slush-molding process combined with ceramic shell casting: 1) a flexible silicone two-piece mold is created from the model (in this example made of clay); the layer of silicone is backed with a rigid mother mold; 2) this reusable mold is disassembled and the model removed; 3) to form the inter-model, molten wax may first be brushed into the interior of the piece mold to ensure that the wax reaches all areas and captures the fine details; 4) the mold is reassembled; the molten wax is poured in and slushed around in order to coat the interior; 5) excess molten wax is poured out; this “slush molding” is repeated until the desired thickness is achieved; 6) the hollow wax inter-model is removed from the mold, imperfections repaired, and details refinished; 7) core pins are pushed through the wax walls and the wax sprue system is fused to the inter-model; 8) an iron armature is inserted into the hollow wax, which is then filled with refractory core material (note: in ceramic shell casting, the core can be a plaster-based investment or the same ceramic shell materials as the outer mold); 9) the inter-model is then coated with a liquid ceramic slurry followed by grains of fused ceramic to provide bulk and a textured surface that will ensure that the next layer of slurry adheres well; once this first layer is dry, the process is repeated (eight to ten times) to create the desired thickness of ceramic shell; 10) when the refractory mold has dried, it is placed upside down and heated rapidly to burn out all traces of wax; it is then placed in a kiln to dry the plaster investment core and sinter the ceramic shell into a sturdy, unified body that can withstand the pressure of the molten bronze; 11) the hot mold is removed from the kiln, turned with the casting cup facing up, and the molten bronze poured into the mold; 12) when the metal has cooled, the ceramic shell casing is broken off of the cast and remains are removed by sandblasting; the bronze sprue system is cut off and the core pins and plaster core removed along with the internal armature; 13) chasing includes polishing, burnishing, and the addition of textures and sharpening of details as needed; 14) as a final step, a chemical patina and/or a coating may be applied. Diagram based on Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). See [Case Study 7](#CaseStudy7). |
|  | **819** | Application of wax slabs on the internal surface of one half of a plaster mold used for a bronze reproduction of the head of the Apollo of Lillebonne during the 2016 CAST:ING meeting, Coubertin foundry, France. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **1108** | Main steps of the indirect wax slab process: 1) a piece mold is formed on the model, composed of smaller pieces to account for the undercuts; 2) the piece mold is removed and sections are lined with thin, warmed sheets (slabs) of wax; 3) the wax parts are joined with a hot tool to form a hollow inter-model, and the surface is reworked as needed; 4) the hollow wax inter-model is ﬁlled with refractory core material and core pins are inserted through the wax and into the core; 5) the wax sprue system is fused to the inter-model in strategic locations with a hot tool; 6) core pins are inserted through the wax into the core and the sprue system is added to the inter-model; 7) the inter-model is invested in a refractory mold; 8) the mold is then heated until dry and all traces of the wax burned out; 9) meanwhile, a simple receptacle that will serve as a crucible is shaped of refractory material; small pieces of bronze and charcoal are placed in the crucible, which is luted to the mold to form an enclosed unit); 10) the mold+crucible is heated with the crucible face-up until the metal is molten; 11) then it is inverted to allow the liquefied bronze to pour quickly into the mold; 12) fettling includes breaking off the refractory mold, removing the core pins, and cutting away the sprue system; 13) chasing may include polishing, burnishing, and the addition of details as needed; the surface color may also be enhanced with inlays, coating, plating, and/or patination. |
|  | **820** | Application of balls of wax on the internal surface of one half of a plaster mold for the bronze reproduction of the head of the Apollo of Lillebonne during the 2016 CAST:ING meeting, Coubertin foundry, France. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **155** | Example of a very regular and thin metallic wall (~2 mm) on a large bronze. See also the hair made on the wax model via the addition of rolled wax threads and rods. Bronze Statue of Hawtar’athat, Yemen, 1st millennium BCE, H. 140 cm (National Museum of Sana’a, Yemen, inv. YM 23206). See {Mille et al. 2010}; {Mille et al. 2012}. |
|  | **708** | Assembled silicone rubber mold of the head and neck of the horse awaiting wax application along with bucket of red casting wax, wax sprues, a casting cup freshly formed in its mold, and brushes for wax application. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **1100** | Hot molten wax is brushed onto the internal surface sections of a plaster mold as part of an indirect lost-wax casting process carried out during the 2016 CAST:ING meeting, Coubertin foundry, France. |
|  | **489** | Diagram of a version of the lasagna technique. 1) a plaster piece mold is built up in sections around the clay model; 2) the reusable mold is disassembled; 3) sections of the mold are lined with sheets of clay that Cellini referred to as “lasagna” and that create the space to be filled eventually by bronze; 4) a fire-resistant clay core is built up around an iron armature to fit snugly into the lasagna-lined mold and dried; 5) the piece mold is disassembled in order to remove the lasagna; 6) the core is baked and reinforced by binding with wires; the fired core and plaster piece mold are assembled; and the armature and mold extension at the base help to preserve the space created by the lasagna; 7) molten wax poured into the space between the core and the piece mold creates the inter-model; when freed from the mold it is reworked to the artist’s liking; 8) the sprue system is joined to the inter-model and invested with refractory mold material; 9) the mold is then heated until dry and all traces of wax are burned out; 10) molten bronze is poured into the baked mold until it is full; 11) when the metal has cooled, the refractory mold is broken away, the armature and core removed, and the sprue system cut off; 12) separately cast parts, such as a base, may be added at this stage, and the surface color may be enhanced by various means, including patination or gilding. Sketch based on Benvenuto Cellini (Italian 1500–1571), Bust of Bindo Altoviti, 1549, H. 85.2 cm (Isabella Stewart Gardner Museum inv. S26e21). See {Bewer and MacNamara 2012}. |
|  | **821** | Application of clay sheets (lasagna) on the internal surface of one half of a plaster mold for the bronze reproduction of the head of the Apollo of Lillebonne during the 2016 CAST:ING meeting, Coubertin foundry, France. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **784** | Diagram depicting a version of the cut-back-core process: 1) a plaster piece mold composed of smaller pieces to account for the undercuts is formed on the model; the sections are held together by an outer mother mold; 2) the piece mold is removed from the model; core support rods and wires are positioned as needed in the partially reassembled empty mold; 3) the mold is fully reassembled and filled with refractory material (here plaster-based) to create a replica of the original model; 4) the surface of the replica is pared down (cut back) to form the core of the mold, thereby creating the space that will be filled first by wax and later by metal; 5) the cut-back core is placed back into the piece mold, suspended in place by the core support rods that also serve as core pins in this example; 6) molten wax is filled into the cavity around the core, thereby creating the inter-model; 7) the inter-model is removed from the mold and reworked as needed; the sprue system is joined to it with a heated tool and the assemblage is invested in a refractory mold; 8) the mold is baked to dry it thoroughly and to burn out all traces of the wax; 9) the mold is filled with molten metal; 10) the bronze is freed of the investment, sprues, and protruding core supports; 11) in the final stages the bronze surface may be refinished with details, then joined to the separately cast arms and base and a patina applied. Diagram based on Michel Anguier (French 1612/14–1686), Melancholy Pluto, before 1699, H. 23.9 cm (Staatliche Kunstsammlungen, Grünes Gewölbe, Dresden, inv. IX.37). See {Bassett and Bewer 2014}. |
|  | **795** | Diagram depicting a version of the piece-mold casting process: 1) a model of the Yu vessel with lid is prepared out of loess (a fine-grained refractory soil found throughout northern China) and baked dry; 2) the piece-mold segments need to account for undercuts in the model; half of the upper part is covered in loess to form the first section of the investment mold; its edge is smoothed and keyed to ensure alignment of the next section; 3) the second section of the mold is built up alongside the first and allowed to dry and harden; the mold segments are carefully removed from the model; 4) in order to make the core, the top two pieces of the mold are reassembled and packed tightly with loess to form a replica of the original model; a base is added; 6) the mold is opened; at this stage additional details can be carved into the face of the mold; 7) the outer surface of the loess replica is cut back (pared down) to create the space that will be filled with molten metal; 8) the three sections of the mold are reassembled around the core and a funnel/gate is cut into the mold; the assembled mold is baked further until dry and filled with molten bronze; 9) the investment mold is removed and the gate cut off; except for some basic removal of flashing and sprues, the surface would be merely polished; 10) the bronze lid and body of the vessel (produced by the same process) are fine-tuned to fit perfectly. |
|  | **833** | Andrew Lacey’s life-cast of a lizard. Top left: the lizard is sprued in the bottom of the mold. Top right: top part of the plaster mold with the lizard still in. Bottom left: detail of the plaster mold once the lizard was partially removed by burning. Bottom right: detail of the cast bronze. The cast of the lizard was made in a mold designed in parts to remove any remaining bones or ash. Had it not been, some of these remains might have gotten lodged in the metal and formed an inclusion that could result in a lacuna in the cast. See [I.3](#I.3). Andrew Lacey (British, b. 1969), \*Life Cast of a Lizard\*, cast by the artist in 2015, Devon, UK, L. 15 cm (Victoria and Albert Museum, inv. NCOL.517-2015). |
|  | **782** | Diagram depicting a version of the direct wax-slab process: 1) the main shape of the griffin head casting model is formed of wax slabs that are cut into their proper shapes; the raised shapes of the upper and lower eyelids are formed by pressing the slabs out, producing recesses on the reverse; 2) the wax elements are joined with a heated tool to form a hollow head; 3) the hollow wax griffin head is filled with a refractory clay core material; the eye cavities are cut out and ledges formed on the interior to support inlays that will later fill the voids; 4) details are added to the wax; these include incised lines around the eyes and a scaly pattern formed with punches; the solid wax tongue, ears, and top knob are joined to the head; 5) the sprue system is joined to the model; 6) the wax model is invested in a refractory mold that is heated until dry and all traces of wax are burned out; the openings in the eyes and the neck act as core extensions, preserving the space between the core and the outer mold; 7) the mold is filled with molten bronze; 8) when cool, the cast is broken out of the mold, and the sprue system is removed; 9) the bronze is then chased and in this example the eyes inlaid. Diagram based on {Mattusch 1990}. |
|  | **822** | Example of the direct wax slab process as seen in Patan, Gujarat, India, in the 1980s. The wax torso of a large statuette is shaped by modeling wax slabs, before adding the core. See {Craddock 2015}; {Furger 2017}. |
|  | **928** | Various images from a Harvard University January-term bronze casting course (2012) led by Francesca Bewer showing the process of carving into a resin-bonded sand mold, and the textures and details on the resulting bronzes. |
|  | **290** | Radiographic detail of the torso of Apollo clearly shows a wax-to-wax joint as a dark ellipse at the junction of the arm to the shoulder (blue). See also the complex armature and notably the transverse rods (orange) going through the main armature rods (red). Apollo and Daphne, probably France, early 18th century, H. 85 cm (Musée Fabre, Montpellier, France, inv. 836.4.86). See {C2RMF Internal Report #37090, 2018}. |
|  | **390** | X-radiograph showing a complex armature made of different sizes of rods and wire (11 mm, 7 mm, and 4 mm in diameter). See also the wax-to-wax joints. A 15 mm Cu filter was needed to keep the same exposure parameters for all the different areas of the sculpture, despite the significant variations in thickness (400kV, 8mA, 15 min. exposure, 3 m source-to-object distance, AA400PB film). Antoine-Louis Barye (French, 1795–1875), Theseus and the Centaur Bienor, cast by Eugène Gonon (1814–1892) in 1877, H. 1.3 m (Musée du Louvre, inv. RF 3882). For daylight photography of the statue see **fig. 395**. See {C2RMF Internal Report 2016b}. |
|  | **687** | The artist beginning the modeling process on a metal armature. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **540** | Overlay of interpretive technical diagram and both X-radiograph and daylight photography showing the wire wrapping the core. Note how complex the image is due to the numerous overlaps, for instance of the drapery. Barthélemy Prieur (French, ca. 1536–1611), Abundance, cast in 1571 by Nicolas Péron, H. 128 cm (Musée du Louvre, inv. MR1681). See [Case Study 5](#CaseStudy5). |
|  | **755** | Detail of an annotated digital X-radiograph showing transverse core pins in both thighs (yellow overlays), one running side to side, the other front to back. Rectangular patches (blue overlays) fill the holes left in the bronze wall when the front-to-back core pins were cut off at the surface and pushed into the hollow bronze cavity. Giovanni Battista Foggini (Italian, 1652–1725), Dancing Faun, ca. 1700, H. 54 cm (J. Paul Getty Museum, inv. 2000.8). |
|  | **321** | Detail of internal surface showing a core pin with the head in the interior, testifying to the use of a process in which the core was set after the wax in the mold. Remains of clay core are visible (top right). Giovan Francesco Rustici (Italian, 1475–1554), Tomb Effigy of Alberto III Pio, Prince of Carpi, ca. 1535, L. 167 cm (Musée du Louvre, inv. MR 1680). See {C2RMF Internal Report 2016a}. |
|  | **388** | X-radiographs showing the influence of lead intensifying screens placed directly in front of and behind the film. Without lead screens (left), the contrast is low. On the right, the addition of the lead reinforcing screens (MX125PB film) reveals technical features, including core pins (some marked with red overlays). Operating conditions for both images are: 260kV, 4mA, 8 min. exposure, 2.5 m source-to-object distance, 2.6 mm Cu beam filtering. Candlestick Representing Samson and the Lion, Lower Saxony, ca. 1175–1225, H. 22 cm (Musée départemental des antiquités de Rouen, France, inv. R.91.23). See {C2RMF Internal Report 2015b}. |
|  | **581** | Endoscope image of the inside cavity revealing a particular type of chaplet. Martin Lefort (French, dates unknown), Justice, 1571, H. 128 cm (Musée du Louvre, inv. MR1682). See {Castelle et al. 2021}. |
|  | **533** | The different types of chaplets for twentieth-century industrial iron sand casting. Each type has a special use: A–F are perforated sheet tin for heavy loads; I–M are for the heavier castings (tons); G–I are the most common types. From {Palmer 1929}, 157, fig. 119. |
|  | **1084** | Sketch of a chaplet firmly wedged between the core and the outer mold, with a protruding point securing it in place in the clay on one side. This is one of many notes that Leonardo made in connection with the casting of the Sforza Horse. Leonardo da Vinci, Madrid Codex II, 1503–5, fol. 156r (Biblioteca Nacional de España, Ms. 8936). |
|  | **979** | Wax inter-model and bronze copy of Antinous (French School) made by Andrew Lacey in 2014. The core extending out of the base will function as a mold extension, tying the core to the investment and reducing the number of core pins needed. In the indirect process, both the wax inter-model and the casting alloy will contribute to the overall shrinkage of the sculpture. This is most noticeable when comparing the original model to the final bronze sculpture. The wax inter-model will shrink by ~2.5–3% in linear dimension and the casting alloy by ~1–1.5%; therefore the final sculpture will shrink by ~4% in total. |
|  | **1065** | Annotated detail of an X-radiograph showing core support rods (yellow overlay) supporting a wax-to-wax joint in the arm (blue overlay). Giovanni Battista Foggini (Italian, 1652–1725), Dancing Faun, ca. 1700, H. 54 cm (J. Paul Getty Museum, inv. 2000.8). See {Fogelman and Fusco 2002}, 238, 357. |
|  | **879** | Annotated X-radiograph of a sand cast. Both Dejanira’s and Hercules’s heads were cast separately and secured at the neck with Roman sleeve joints (yellow overlay). Roman joints also secure Dejanira’s proper right arm as well as Hercules’s proper left arm. There is an internal seam line in Dejanira’s left shoulder where the separately formed core in the arm abuts the core used in the torso (blue line). Lanterns can be seen in the torso and the proper left arm (red overlays). Charles Crozatier (French, 1795–155), Hercules freeing Dejanira from the Centaur Nessus, Paris 19th century, after Adriaen de Vries (Netherlandish, 1556–1626), H. 78.5 cm (Rijksmuseum, Amsterdam, inv. BK-1957-2). |
|  | **25** | Sprueing system on a reproduction casting. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.149). See **video 8**. |
|  | **811** | Alignment of gates and vents for the circulation of molten bronze and gases during the casting. {Mariette 1768}, 78, plate II detail, showing Edme Bouchardon (French, 1698–1762), Louis XV, cast in 1758 by Pierre Gor (French, 1720–1773), H. 520 cm. After {Desmas 2014}. |
|  | **923** | Bronze suspended from the pouring cup within a modern mount. After Martin Van Den Bogaert (Desjardins) (Dutch, 1637–1694), Louis XIV on Horseback, cast by Roger Schabol (Dutch, d. 1727), early 1700s, H. 52.4 cm (Statens Museum for Kunst, Copenhagen, inv. KMS 5403). |
|  | **217** | Sculpture made of Algerian onyx-marble, bronze, gilt bronze, enamel, and amethyst eyes, and white marble socle. Sculptors such as Cordier took advantage of enamel to add color, as in this draped head covering. Charles-Henri-Joseph Cordier (French, 1827–1905), \*The Jewish Woman of Algiers\*, Paris, 1862, H. 90.2 cm (Metropolitan Museum of Art, European Sculpture and Decorative Arts Fund, 2006, inv. 2006.113a–c). |
|  | **777** | Detail of head showing how the vivacious modeling of the curls in the wax model has been captured in the bronze. Barthélemy Prieur (French, ca. 1536–1611), Funerary Genius, 1583–85, L. 109 cm (Musée du Louvre, inv. MR 1685). See {Bewer, Bourgarit, and Bassett 2009}; {Seelig-Teuwen, Bourgarit, and Bewer 2014}. |
|  | **778** | Detail of chest showing the modeling of the ribs in wax by hand. Barthélemy Prieur (French, ca. 1536–1611), Funerary Genius, 1583–85, L. 109 cm (Musée du Louvre, inv. MR1685). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}; {Castelle 2016}. |
|  | **926** | Reverse of panel showing evidence of sprues and working from the back of the wax model. The detail shows an area around the edges of a hollow portion that has been reinforced with small masses of soft wax pressed around the edges. They correspond to the area where the hollow protruding figure of David meets the background of the relief. The malleable material also captured partial fingerprints. Lorenzo Ghiberti (Italy, ca. 1381–1455), David and Saul panel in the \*Gates of Paradise\*, left door, H. 518 cm (design begun after 1425; installed 1452 (Museo dell’Opera del Duomo, Florence, inv. 2005/905). See {Bewer, Stone, and Sturman 2007}. |
|  | **5** | Detail of cornucopia showing tool marks in the wax (green overlay) Marks of metal hammering are also visible (orange arrows). Barthélemy Prieur (French, ca. 1536–1611), Abundance, cast in 1571 by Nicolas Péron, H. 128 cm (Musée du Louvre, inv. MR 1681). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}. |
|  | **7** | Detail of neck that preserves the raw tool marks made on the wax model (arrows indicate the direction of the stroke). The finer striated marks in the bottom right corner may have been made in the metal with a file. Barthélemy Prieur (French, ca. 1536–1611), Funerary Genius, 1583–85, L. 109 cm (Musée du Louvre, inv. MR 1685). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}. |
|  | **902** | Underside of two reduced-size casts showing the characteristic, more angular inner surface of a sand cast produced by the pared-down core (top), and the softer forms of a lost-wax cast (bottom). Auguste Rodin (French, 1840–1917), \*Burgher of Calais: The Man with the Key, Jean d’Aire\*, after 1895, H. 47 cm (Harvard Art Museums / Fogg Museum, Bequest of Grenville L. Winthrop, inv. 1943.1154 [top], and modern cast from private collection [bottom]). |
|  | **430** | View underneath showing consecration offerings. See also the raised ridges (arrows) indicating wax-to-wax joints. Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **1104** | Detail of the inside of the bronze showing a core pin hole (diameter 2.5 mm) made in the wax inter-model. The softened rim of the hole was created as the warmed core pin was pushed through the wax. Brush marks and fingerprints are further evidence of the production of the wax inter-model. Andrew Lacey (British, b. 1969), \*Ashen\*, 2021, H. 192 cm (artist’s collection). |
|  | **927** | Detail of the lower portion of a lost-wax after-cast of a Renaissance partially gilded silver plaquette as cast. The myriad small bronze spherules (see overlay) result from air bubbles in the poorly applied plaster-based investment slurry, which settled on the surface of the wax inter-model. Francesca Bewer after-cast made from an electrotype copy (date unknown) after Galeazzo Mondella (Italian, 1467–1528), Sacra Conversazione, ca. 1510, H. 13.9 cm (Kunsthistorischesmuseum, Vienna, inv. Kunstkammer, 1107). |
|  | **1060** | Detail of the open back of the bust, where spheres of bronze are the result of air bubbles from the plaster core trapped against the wax casting model (some examples circled). Jean-Baptiste Pigalle (French, 1714–1785), Bust of Denis Diderot, 1777, H. 52.2 cm (Musée du Louvre, inv. RF 1396). |
|  | **799** | View of internal cavity showing details of the translation into bronze of porosities created by organic materials incorporated in the core that were close to the surface and replaced by the metal. Barthélemy Prieur (French, ca. 1536–1611), Funerary Genius, Christophe de Thou Monument, 1583–85, L. 109 cm (Musée du Louvre, inv. MR 1685). |
|  | **881** | Interior detail of a welding line that joins two large sections of a lost-wax cast base (blue overlay). Note the characteristically jagged-edged flashing due to clay or plaster core that formed perpendicularly to the bronze walls (red arrows). Henry Moore (British, 1898–1986), \*Seated Woman\*, designed 1958–59, cast 1975, H. 203.2 cm (J. Paul Getty Museum, inv. 2005.117.3). See **fig. 203** for a general view. |
|  | **122** | Detail of the underside of the tomb effigy showing drips on the inner edge that were formed through use of a hot tool on the wax model (green marks), the network of flashing due to cracks in the core (yellow marks), and short, straight, crisp chisel marks (red marks) created during removal of flashing and of the clay core (pink overlay). Giovan Francesco Rustici (Italian, 1475–1554), Tomb Effigy of Alberto III Pio, Prince of Carpi, ca. 1535, L. 167 cm (Musée du Louvre, inv. MR 1680). See {C2RMF Internal Report 2016a}. |
|  | **1061** | The underside of the base reveals numerous features indicative of sand casting: the overall angular and geometric contours of the base (red arrows); seam lines likely formed between sections of the core (yellow lines); the larger seam lines [flashing] appear to have been chiseled down); nuts on threaded rods used to secure the separately cast figures (white overlay); hammering to better align the joined sections (green overlay). Traces of the sand mold are present (examples overlaid in blue). Francois-Auguste-Hippolyte Peyrol (French, 1856–1929), Indian Fighting Cougar (French title according to the inscription plaque is \*La Lutte Pour La Vie\*), cast in France, marked Peyrol foundry, inscription date 1933 (probably cast prior to 1927, when the foundry closed), H. 75 cm (collection of George Syrmos). |
|  | **824** | Bronze reproduction of the head of the Apollo of Lillebonne made by sand casting during the 2016 CAST:ING meeting, Coubertin foundry, France, before any repairing. See the rough as-cast surface representing the texture of the sand mold, and the stepped linear feature following the piece-mold joint line. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **375** | X-radiograph showing a wax-to-wax joint on the right arm (red dotted line), as revealed by the discontinuity in the metal wall thickness (blue overlay). Note that making precise measurements of wall thickness from radiographs may be difficult, as the external edge may not be visible if overexposed (yellow line). As a consequence, the metal wall thickness may be up to 30% greater than that inferred from the radiograph (blue overlay). After Giambologna (Netherlandish, 1524–1608), Hercules, ca. 1580, cast in Italy, Germany, or the Netherlands, 17th century or later, H. 43 cm (Musée des beaux arts d’Angers, France, inv. 2003-1-180). See {C2RMF Internal Report 2018b}. |
|  | **848** | Annotated X-radiograph showing numerous small circular holes (red dots) testifying to the use of transverse core pins passing through the horse’s body from one side to the other. See also the long wax joint running the length of the horse (green lines). Horse and Rider, Italian, 16th century, H. 33 cm (Musée des beaux arts d’Angers, France, inv. 2003-1-182). See {C2RMF Internal Report 2018b}. |
|  | **399** | Annotated X-radiograph illustrating a number of technical features: 1) gaps in the core; 2) screw repair; 3) repair patch; 4) mechanical assembly; 5) cast-on repairs; 6–7) variation of thickness of the metal wall due to core shift; 8) core juncture; 9) wax flashing; 10) internal core support. Venus déhanchée, northern Europe, 17th century, H. 45 cm (Musée des beaux arts d’Angers, France, inv. 2003-1-200). See {C2RMF Internal Report 2018b}. |
|  | **13** | The horse fittings were added as wax rods on the wax model. Aquamanile in the Form of a Knight on Horseback, Lower Saxony, Germany (probably Hildesheim), ca. 1250, H. 37.3 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1492). See {Dandridge 2006}. |
|  | **166** | Example of direct wax additions on a wax model, notably the attribute in the left hand. Statuette of Jambhala, central Java, first half of the 9th century, H. 28 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3814). See {Mechling et al. 2018}. |
|  | **463** | The height of this whole statue (probably an emperor) is 3.3–3.5 m. While the overall shape was produced using the indirect lost-wax process, the decoration was created by adding wax rods and threads directly to the wax model. Colossal Foot of Clermont-Ferrand, Roman (Gaule), early 2nd century CE, L. 58 cm (Musée de Clermont-Ferrand, Gaule). See {Darblade-Audoin and Tavoso 2008}. |
|  | **769** | The open lattice patterns that decorate the inner walls of this small, directly cast, lost-wax structure reproduce the carefully applied wax threads that were laid over the carbon-rich core. Artist unknown, partial grouping of architectural structures on bronze base, Dhoka, Indian (?), 20th century, H. 13.3 cm (private collection). |
|  | **1054** | Detail of vine leaf and grapes in the figure’s right hand that have clearly been modeled in wax. Barthélemy Prieur (French, ca. 1536–1611), Abundance, cast in 1571 by Nicolas Péron, H. 128 cm (Musée du Louvre, inv. MR 1681). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}; {Castelle et al. 2021}. |
|  | **767** | This small pair of human figures were modeled directly in wax. The heads were fashioned out of balls of soft wax from which the noses pinched out. The breasts are small, flattened balls of wax pressed onto the torsos. The legs were rolled into sausages and joined at the bottom on the rounded base. The group was clearly cast head-down in the mold, as the base is formed by the remains of the metal that puddled at the bottom of the casting cup. Group of Two Human Figures, Syro-Hittite, 15th–13th century BCE, H. 7.4 cm (Harvard Art Museums / Arthur M. Sackler Museum, gift of Benjamin and Lilian Hertzberg, 2004.205). See {Lie and Bewer 2014}, 46. |
|  | **107** | Detail of the back of the right knee showing the remains of seam lines from the piece molds when forming the wax inter-model (see overlay). Attributed to Hubert Le Sueur (French, ca. 1580–1658), Medici Venus, H. 150 cm (Musée du Louvre, inv. MR 3278). See {Castelle 2016}. |
|  | **685** | Bronze reproduction by slush molding of the head of the Apollo of Lillebonne made during the 2016 CAST:ING meeting, Coubertin foundry, France. Despite its complex shape, the cavity on the left cheek does not stem from any exogenous material fallen in the melt, but rather from the thinness of the wax model in this area. The vertical seam lines in the middle of the forehead are a direct reproduction of the mold lines on the wax model (see **fig. 74**). The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **686** | Wax reproduction of the head of the Apollo of Lillebonne made during the 2016 CAST:ING meeting, Coubertin foundry, France. This wax was obtained by slush molding in a plaster piece mold. All the mold lines (seam lines) are clearly visible. Note the distortion of the model due to imperfection in the piece-mold assemblage. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **878** | Raised seam lines appear to correspond to traces of the piece mold used to create a plaster model that was then used in an indirect process. Camille Claudel (French, 1864–1943), Torso of a Crouching Woman, model ca. 1884–85, cast by 1913, H. 35 cm (J. Paul Getty Museum, inv. 2018.32). |
|  | **681** | Juxtaposition of these two indirect lost-wax casts shows how their assemblage from separate wax parts—in this case, the limbs and torso (as confirmed by X-radiography)—can result in slight variations in their postures. Willem van Tetrode (ca. 1525–1580), Striding Warrior, 1562–65, H. 40 cm (Collection of Mr. & Mrs. J. Thomilson Hill, New York [left]) and H. 39.4 cm (Hearn Family Trust, New York [right]). See {Bewer et al. 2003}. |
|  | **922** | Detailed image of a small area of the chin showing flashing in the refractory mold that has been filed down. The lines are so angular, they look like the intersecting lines of a mold. Andrew Lacey (British, b. 1969), \*Head of Henry Tonks\*, cast by the artist in 2015, H. 17 cm (artist’s collection). |
|  | **770** | Underside of the Theseus and Antiope group showing the long marks that the artist’s fingers produced in pulling up a mound of fresh clay from the slab that formed the core for the base. Adriaen de Vries (Netherlandish, 1556–1626), Antiope and Theseus, ca. 1600–1601, H. 95 cm (Royal Collection, Buckingham Palace, London, inv. RCIN 57961). See {Bewer 1998}, 70; {Bewer 2001}. |
|  | **1037** | Annotated composite X-radiograph. Note in particular the continuous armature that extends throughout the direct lost-wax cast. Adriaen de Vries (Netherlandish, 1556–1626), Juggling Man, ca. 1615, H. 76.8 cm (J. Paul Getty Museum, inv. 90.SB.44). |
|  | **823** | X-radiographs of experimental casts after the same model of Apollo using three different lost-wax casting processes. The heads were produced by beginners during the 2016 CAST:ING meeting at the Coubertin foundry, France, and can therefore not claim to be representative of features in expertly cast historical bronzes, but present a few noteworthy features. 1a–b) Side and frontal views of the same head produced by the slush molding process. They show the relatively even thickness of metal wall that follows the contours of the molding. The frontal view shows the drips that formed in the neck (turquoise overlay) on the internal surface when the excess liquefied wax was poured out of the reusable mold. The solid spheres on the top of this and the other casts are from air bubbles trapped along the inner surface when the fresh plaster-based core slurry was poured into the mold (orange overlay dots). 2) Unlike the head in 1a, this cast of the Apollo head is more uneven, as seen in particular in the facial area, where the flattened shape of the inner surface is the result of a rather thick clay slab (the “lasagna”) that was initially laid into the reusable mold to create the negative space to be filled by the bronze. 3) The frontal view of the third experimental cast shows the overall even thickness of the metal wall that results from the use of the thin wax slabs pressed into the mold. The joint of several of the wax slabs runs vertically down the face and back of the head (blue overlay lines). See also **fig. 121**. The height of the casts is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **1073** | Lion appliqué, probably discovered in Tamna, Yemen, third quarter of the 1st century BCE, H. 67 cm (National Museum of Sana’a, Yemen, inv. YM36526). See {Mille et al. 2010}. |
|  | **1074** | Rear view showing the bent metallic walls at the edge that are considered evidence of the use of wax slabs. Lion appliqué, probably discovered in Tamna, Yemen, third quarter of the 1st century BCE, H. 67 cm (National Museum of Sana’a, Yemen, inv. YM36526). See {Mille et al. 2010}. |
|  | **158** | Detail showing the marks of a tool used to work the interior surface of the wax inter-model. Zoomorphic Figure Evoking a Griffin, France, early–late antiquity, H. 26 cm (Musée de la préhistoire du Grand-Pressigny, France, inv. 2008.001.0001). See {C2RMF Internal Report 2008a}. |
|  | **773** | Rear surface of a fragment of the dolphins showing a fingerprint (yellow overlay) and the elongated traces made by a fine-toothed tool or finger (white arrows indicate the direction of the strokes) drawn along the inside of the wax model. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). See technical sketch, **fig. 367**. |
|  | **1093** | This internal view of a small arm shows an extant wire core pin and the uneven blobby accretions at its point of contact with the inner surface. These occurred during casting, with the molten-metal-filled gaps created in the core when the wire was pushed through core-filled wax model, causing some localized breakdown. Andrew Lacey (British, b.1969), \*Hand\*, 1998, H. 18 cm (private collection). |
|  | **772** | Rear surface of the head of the front dolphin showing sprues added on the wax model (yellow overlay). The wax model of the head was made of several pieces joined together at the juncture of the upper and lower lips, and also at the rotrum. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). See technical sketch, **fig. 367**. |
|  | **802** | View from the inside of a bronze reproduction of the head of the Apollo of Lillebonne made during the 2016 CAST:ING workshop, Coubertin foundry, France, showing the typical smooth flowing surface of slush-molding casts. The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **742** | Inside view of the horse head showing tide lines from the flow of liquid wax captured on the inner surface of the bronze. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **919** | General view and detailed image of the work’s reverse showing the brushstrokes from painting in liquefied wax. Andrew Lacey (British, b. 1969), \*Study for Saint Sebastian with Bullet Holes\*, cast by the artist in 2017, H. 60 cm (artist’s collection). |
|  | **804** | Annotated X-radiograph showing the very thin and even metal walls (1–2 mm, red arrows). See also the large core flashing at the level of the belly (white feature shown by the green arrow). Maitreya, Khmer, pre-Angkor, 8th century, H. 46 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 3321). See {Bourgarit et al. 2003}. |
|  | **805** | X-radiograph showing the very thin and even metal walls (2 mm). Bronze Statue of Hawtar’athat, Yemen, 1st millennium BCE, H. 140 cm (National Museum of Sana’a, Yemen, inv. YM 23206). See {Mille et al. 2010}. |
|  | **1101** | X-radiograph of the forearm of a monumental Roman statue cast by the lost-wax process. The long, dark, linear area corresponds to a thinning in the original wax model where wax slabs were not joined all the way through. The area would have been filled with core material and the imperfection was thus translated into bronze. Arm of Essegney, Roman, Essegney, France, probably 2nd–3rd century CE, L. from hand to elbow 43 cm (Musée départemental d’art ancien et contemporain d’Epinal, France, inv. M0536\_2005.2.1). See {Caumont et al. 2006}. |
|  | **776** | View of underside showing the angular contours of the interior, typical of the cut-back-core process. Gaspard Marsy (French, 1624–1681), Boreas Abducting Orithyia, probably cast late 18th century, H. 55.2 cm (J. Paul Getty Museum, inv. 74.SB.18). See {Bassett and Bewer 2014}. |
|  | **136** | Tool marks testifying to the cutting back of the core. Shown here is the back view of a bronze fragment of the Vendôme Column. This may be related to what the founder of most of the Vendôme Column bronzes, Jean-Baptiste Launay (French, 1768–1827), described as \*amaigrissement du noyau\* (core thinning). Various French sculptors, Vendôme Column, 1805–10, dismantled 1871, re-erected 1873–75, H. 44 m (Place Vendôme, Paris). See {Launay 1827}, 1:XV. |
|  | **818** | Inside view of a bronze reproduction of the head of the Apollo of Lillebonne made by the lasagna process during the 2016 CAST:ING meeting at the Coubertin foundry, France. The outer contours of the hair are not at all visible on the simplified interior of the head. See the working marks of the clay sheet (lasagna), and particularly the thick joint between the two main sheets crossing the length of the head (red arrows). The height is 18 cm (two-thirds of the original size). Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **901** | View of the interior of a bust showing the wire mesh that would have bound the core and is now embedded in the inner metal surface of the cast. Benvenuto Cellini (Italian, 1500–1571) Bust of Cosimo I, 1546–47, H. 110 cm (Museo Nazionale del Bargello, Florence, inv. 358 Bronzi). See {Bewer and MacNamara 2012}. |
|  | **546** | Overlay of interpretive technical diagram and both X-radiograph and daylight photography. Martin Lefort (French, dates unknown), Justice, 1571, H. 128 cm (Musée du Louvre, inv. MR1682). See [Case Study 5](#CaseStudy5). |
|  | **787** | An example of life-casting in which the model was entirely burned out in the process. Andrew Lacey (British, b. 1969), \*A Modern-Day Thistle\*, cast for the artist’s own experimental research, 2015, H. 3.5 cm (artist’s collection). |
|  | **788** | The saddle belt is cast “from life” from a woven band that was added onto the wax model’s belly. Andrea del Verrocchio (Italian, ca. 1425–1488) and Alessandro Leopardi (Italian, ca. 1465–1512), Equestrian Monument of Bartolomeo Colleoni, Venetian, 1479–96, over life size (Piazza SS Giovanni e Paolo, Venice). See general view of the monument, **fig. 100**. |
|  | **900** | Andrea del Verrocchio (Italian, ca. 1435–1488) (model of horse) and Alessandro Leopardi (Italian, ca. 1465–1512 (finished model and cast), Equestrian Monument of Bartolomeo Colleoni, 1479–96, over life size (Piazza SS Giovanni e Paolo, Venice), after 2006 conservation by Giovanni and Lorenzo Morigi. |
|  | **477** | Detail of a gilded brass relief figure showing gouge marks from the carved, hollow wooden pattern and the granular surface of the sand mold. Relief figure of Benjamin Franklin, purportedly cast by Paul Revere (American, ca. 1735–1818) after a wood model by Simon Skillen, from Joseph Pope’s (American, 1750–1826) Grand Orrery, 1776–87, H. 31 cm (Collection of Historical Scientific Instruments, Harvard University, inv. 0005). |
|  | **914** | This chef-modèle has been cast in four sections (here assembled by way of interlocking pins, ridges, and slots) so as to provide more manageable segments to be sand molded and cast separately. Antoine-Louis Barye (French, 1795–1875), Lion and Serpent (No. 2), chef-modèle cast by Victor Paillard, ca. 1858, H. 18.4 cm (Walters Art Museum, Baltimore, inv. 27.92). |
|  | **915** | Dismantled chef-modèle. The piecing is characteristic of sand casting of complex forms. Antoine-Louis Barye (French, 1795–1875), Lion and Serpent (No. 2), chef-modèle cast by Victor Paillard, ca. 1858, H. 18.4 cm (Walters Art Museum, Baltimore, inv. 27.92). |
|  | **1033** | Detail of an experimental casting showing sprue ends and core pins. It also shows the coarse, as-cast surface that preserves the V-shaped incised lines of the mane made in the wax model. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **484** | Chasing by punching over fire-skin and casting imperfections. Note the surface that has bonded with the white investment. In-process detail of a reconstruction by Andrew Lacey (British, b. 1969) of one of the so-called Rothschild Bronzes, attributed to Michelangelo Buonarroti (Italian, 1475–1564), H. 91.2 cm (private collection). See {Lacey 2018}. |
|  | **478** | Detail of the reverse of a gilded brass relief figure shows the grainy texture of the sand mold, the gouge marks of the original carved model that were replicated in the bronze, as well as the patched, brazed repairs with flux damage. Relief figure of Benjamin Franklin, purportedly cast by Paul Revere (American, ca. 1735–1818) after a wood model by Simon Skillen, from Joseph Pope’s (American, 1750–1826) Grand Orrery, 1776–87, H. 31 cm (Collection of Historical Scientific Instruments, Harvard University, inv. 0005). |
|  | **796** | View from underside showing the angular shapes of the inner surface that are characteristic of pared-down sand-cast cores. As is also typical with sand casts, the group was made in pieces and assembled in the metal. None of these joints are visible from the outer surface. Antoine-Louis Barye (French, 1795–1875), Lion Devouring a Boar, ca. 1865, H. 16.9 cm (Harvard Art Museums / Fogg Museum, The Henry Dexter Sharpe Collection, inv. 1956.150). For a general view see **fig. 108**. |
|  | **794** | This work was cast in several parts and then bolted together in the metal. The chasing perfectly conceals any trace of the assemblage, which only becomes apparent from the underside (see **fig. 107**). Antoine-Louis Barye (French, 1795–1875), Lion Devouring a Boar, ca. 1865, H. 16.9 cm (Harvard Art Museums / Fogg Museum, The Henry Dexter Sharpe Collection, inv. 1956.150). |
|  | **526** | Inscription on the inner surface of the bust: “A. Rodin” stands for Auguste Rodin. It has been marked on the sand core and thus appears in relief on the bronze. Auguste Rodin (French, 1840–1917), \*Victor Hugo\*, reduction sand casting by Eugène Rudier (French, 1875–1952), 1883–92 for the reduction, cast in November 1916, H. 38.4 cm (Galerie Univers du Bronze, Paris). |
|  | **999** | Annotated back view without the lid indicating the location of the seam lines. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1000** | Annotated top view without the lid, indicating the location of the seam lines. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1001** | Annotated view of the underside indicating the location of the seam lines created at the joints of the loess piece-mold. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1002** | Annotated frontal view indicating the location of the seam lines. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1004** | Annotated three-quarter view of the lid indicating the location of the seam lines. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1006** | Annotated view from above of the lid indicating the location of the central seam line. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1010** | Hand sketches mapping the piece mold sections used to create the \*huo\*. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1011** | Hand-sketches mapping the piece mold sections used to create the \*huo\*. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **921** | General view and details the work’s inside showing tool marks that indicate the core has been shaved down. This was done using a coarse-toothed tool, hence the parallel lines (top right). Other singular lines were used to define either depth that was needed to cut back or to sketch directly onto the core the design or form of the head/features (bottom right). A flat spatula was also used to scrape the surface of the core back (bottom left). Andrew Lacey (British, b. 1969), untitled head, cast by the artist in 2017, H. 31 cm (artist’s collection). |
|  | **826** | The repair patches linked to the armatures used for casting the main section of the bronze pedestal are visible on the external surface (blue squares). Francesco Primaticcio (Italian, 1504–1570), Laocoön and His Sons, 1542, H. 191 cm (Musée national du château de Fontainebleau, France, inv. MR 3290). See {Castelle 2016}. |
|  | **801** | Annotated X-radiograph shows the core pins under the shoulders (teal overlays). Spinario, northern Italy (Padova?), first quarter of the 16th century, H. 15.5 cm (Musée des beaux arts d’Angers, France, inv. 2003.1.188). See {C2RMF Internal Report 2018b}. |
|  | **633** | X-radiographic sequence of a two-thirds-scale bronze reproduction of the head of the Apollo of Lillebonne showing the core-pin holes that have been left unplugged (black spots) and an attempt to repair one of these holes: a rectangular shape has been carved around the hole in the metal but has been left unpatched (dark-gray rectangular shape on the left side of the neck). Click on the image to spin. Two-thirds-scale reproduction using the indirect wax-slab process during the 2016 CAST:ING meeting, Coubertin foundry, France. Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **1062** | Four types of core supports used to hold the core in place during the pour: 1) core pins; 2) transverse core pin; 3) chaplets; 4) mold extension. |
|  | **1066** | Detail of proper left side of torso. The square cast-in patch (yellow overlay) is an original repair of a hole left during casting by the presence of a mold extension. After Leone Leoni (Milanese, 1509–1590), Emperor Charles V, Innsbruck, second half of the 16th century, H. 109 cm (National Gallery of Art, Washington, DC, Samuel H. Kress Collection, inv. 1952.5.104). See {Smith and Sepponen 2019}. |
|  | **905** | Detail showing the sprue remains shaped as rolls of wax preserved on the top and back of the head (see overlay). The artist left these intact on the finished bronze as subtle evidence that the complex sculpture was cast in one piece—an extraordinary feat. Adriaen de Vries (Netherlandish, 1556–1626), Farnese Bull, 1614, H. 103.5 cm (Schlossmuseum, Gotha, Germany, inv. P 50). See {Bewer 2001}. |
|  | **577** | Patches used to repair casting flaws on the right arm are made of unalloyed copper. They were less corroded during burial than the surrounding tin bronze. This phenomenon is probably due to differences of metallurgical state and subsequent porosity: the patches are hammered and much less porous than the primary cast. Reclining Vishnu, West Mebon (Khmer), 12th century, L. 220 cm (National Museum of Cambodia, inv. Ga 5387). See {CAST:ING 2018}. |
|  | **448** | X-radiograph of frontal view, showing that the figure is cast solid. The concentration of porosity in the legs supports the hypothesis of an upside-down casting. Ten-Armed Avalokiteśvara, Java, first half of the 9th century, H. 34 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3816). See {Mechling et al. 2018}. |
|  | **1081** | Annotated X-radiograph. Porosity at the bottom may indicate that the sculpture was cast upside down (blue overlay). Note also the Roman joints (red lines). Divinity of Tara blanche, Tibet, 17th century, H. 65 cm without base (Musée National des arts asiatiques – Guimet, France, inv. MA 12495). See {C2RMF Internal Report 2012}. |
|  | **1086** | Fine lines scratched through the paint-like patina are from mold making, so-called \*surmoulage\* lines. Attributed to Hans Mont (Flemish, ca. 1545–after 1585), Mars and Venus, 1580, H. 53.9 cm (J. Paul Getty Museum, inv. 85.SB.75). |
|  | **827** | Detail of right shoulder showing white lines, probably drawn before molding. Francesco Primaticcio (Italian, 1504–1570), Laocoön and His Sons, 1542, H. 191 cm (Musée national du château de Fontainebleau, France, inv. MR 3290). See {Castelle 2016}. |
|  | **683** | Detail of the rear of the Matilda statuette showing different tool marks. The wider striations on the right and bottom were most likely made in the clay model. The finer parallel lines coming down on the left at a diagonal in the fold appear to have been made at the wax stage with a finer-toothed tool. After a model by Gian Lorenzo Bernini (Italian, 1598–1680), Countess Matilda of Tuscany, ca. 1633–34, H. 40 cm (Harvard Art Museums / Fogg Museum, partial gift of Max Falk and partial purchase through the Director’s Acquisition Fund, 1998.1). See {Bewer 1999}. |
|  | **654** | Periodic table of the elements. |
|  | **466** | A detail of the equilibrium phase diagram of the copper-tin (Cu-Sn) system shows the different phases that may exist in the microstructure of such an alloy depending on the temperature (vertical axis), and the weight percentage of tin in the alloy (horizontal axis). In pure copper, Cu atoms are aligned in a face-centered cube: this is the alpha (α) phase (see **fig. 139**). The delta (δ) phase forms when there is more than ~20 wt% tin. This face-centered cubic phase is responsible for the specific acoustic properties of bells. The diagram also indicates melting temperatures depending on the alloy composition. For example, an alloy with 10% tin melts fully at ~1000°C, once the liquidus line is passed, as shown by the red dotted lines. It solidifies fully at ~830°C, once the solidus line is crossed. |
|  | **653** | Cast coupons made of tin bronzes and brasses showing that zinc has a greater impact on the color than tin. The image of the polished samples was created on a flatbed scanner. |
|  | **652** | Synthetic samples of tin bronzes from 1 wt% tin (top left) to 20 wt% tin (bottom right), showing the evolution of color. Bronze plates, 5 × 6 cm, were cast by Frank Willer/LVR-Landesmuseum Bonn as part of the experimental archaeology for a research project on Roman large bronzes (see {Willer, Schwab, and Mirschenz 2017}). The pieces were polished with pumice stone to enable a clearer perception of the actual color of the alloy with as little reflection as possible. Photograph using neutral studio strobes. |
|  | **467** | Example of how the mechanical strength of bronze allows large offsets (here, the right leg and arm). Pierre Biard I (French, 1559–1609), Fame, ca. 1607, H. 134 cm (Musée du Louvre, inv. LP361). See {C2RMF Internal Report 2017}. |
|  | **470** | Side-by-side view of the Ephesian bronze Athlete, Roman, copy after Greek original, last quarter 4th century BCE, H. 193 cm (Kunsthistorisches Museum Vienna, Collection of Greek and Roman Antiquities, inv. VI 3168), and the Florentine marble Apoxyomenos, 2nd century CE, H. 193 cm (Gallerie degli Uffizi, Florence, inv. 100). Both appeared the 2015 exhibition \*Power and Pathos: Bronze Sculpture of the Hellenistic World\*, Palazzo Strozzi, Florence. Although the extension of the limbs is less dramatic than on other statues, the two arms are secured by a strut on the marble statue but not on the bronze. |
|  | **471** | The armature for this sculpture was removed after casting. The Horse and Jockey from Artemision, found at Cape Artemision, Greece, ca. 150–146 BCE, H. 210 cm (National Archaeological Museum of Athens, inv. X15177). |
|  | **472** | The original armature for this sculpture was removed after casting. A modern structural one has been added to support the fragmentary figure. Dancing Satyr, origin unknown, late 4th–mid 1st century BCE, H. 200 cm (Museo del Satiro, Mazara del Vallo, Italy). |
|  | **465** | Diagram showing how atoms of copper are stacked within a cube. The black dots represent the cores of the atoms; they are located on each corner of the cube and at the center of each face. This crystalline structure is called face-centered-cubic (FCC). After {Scott 1991}, 1, fig. 2. |
|  | **649** | Digital micrograph showing a dendritic microstructure as seen on the corroded surface. Auguste Rodin (French, 1840–1917), \*The Burghers of Calais\*, 1885–89, cast in 1926 at the Alexis Rudier foundry by Eugène Rudier (French, 1875–1952), H. 217 cm (Musée Rodin, inv. S.00450). |
|  | **925** | Touching the surface has removed the patina and revealed the grains of the microstructure of the cast metal by natural etching, as seen in the detail on the right. Paul Landowski (French, 1875–1961), Michel de Montaigne, ca. 1931, cast by Didier Landowski (French, b. 1940) at the Blanchet-Landowski foundry in 1989, H. 200 cm (Ville de Paris, place Paul-Painlevé). |
|  | **452** | Bright field photomicrograph of an etched cross section showing the dendritic microstructure of the primary casting. The outlines of dendrites appear brown; the interdendritic space is filled with phase alpha + delta (eutectoïd composition) together with nodules of lead (gray oval shape) and various inclusions. The Youth of Agde, France, 1st century CE, H. 140 cm (Musée de l’Ephèbe et d’Archéologie Sous-Marine de la Ville d’Agde, France, inv. 839). See **fig. 561** for a general view. See {Mille 2012}. |
|  | **453** | Backscattered electron micrograph of a polished cross section showing the dendritic microstructure of the primary casting. The outlines of dendrites appear dark gray; the interdendritic space is filled with phase alpha + delta (eutectoïd composition) and various inclusions (light gray) as well as nodules of lead (white oval shape). The Youth of Agde, France, 1st century CE, H. 140 cm (Musée de l’Ephèbe et d’Archéologie Sous-Marine de la Ville d’Agde, France, inv. 839). See **fig. 561** for a general view. See {Mille 2012}. |
|  | **462** | Diagrams of two types of common metallographic microstructures of copper alloys. Left: in the dendritic microstructure characteristic of a cast alloy, the dendrites are enclosed by the boundaries of forming grains; right: in the fully recrystallized microstructure, the hexagonal grains are equiaxed. From {Scott 1991}, 7, figs. 11a and 11c. |
|  | **464** | Bright field photomicrograph of an etched polished cross section of a repair filling a core-pin hole. The dendritic microstructure shows that the repair was cast on. The large curved dendrites of the alpha phase (yellow to pink) are marked by a strong primary chemical segregation (known as zoning) between the center of the dendrite (pink) and its periphery (yellow). Colossal Foot of Clermont-Ferrand, Roman (Gaule), early 2nd century CE, L. 58 cm (Musée de Clermont-Ferrand, France). See {Darblade-Audoin and Tavoso 2008}. |
|  | **468** | Bright field photomicrograph of an etched polished cross section of a weld on a large bronze fragment. Three zones may be distinguished: the primary cast, the heat-affected zone (HAZ), and the welding zone. The joining zone is indicated (white dotted line). Fragment from the Hoard of Evreux, France, 1st century CE, L. 14 cm (Musée d’Evreux, France, inv. 4864). See {Azéma et al. 2012}; {Azéma and Mille 2013a}. |
|  | **469** | Bright field photomicrograph of an etched polished cross section of a weld on a large bronze fragment. Detail of the heat-affected zone (HAZ) due to flow fusion welding showing the recrystallized microstructure. Fragment from the Hoard of Evreux, France, 1st century CE, L. 14 cm (Musée d’Evreux, France, inv. 4864). See {Azéma et al. 2012}; {Azéma and Mille 2013a}. |
|  | **474** | Bright field photomicrograph of an etched polished cross section of a Roman Cornu. Grains are quite large (50–100 µm equivalent diameter) and homogeneous in size with a regular polygonal morphology. Thermal twins are frequent, as seen by the thick straight dark lines crossing the grains from one boundary to another. A number of features, including metal composition and microstructure, have proved to be very similar across the five investigated \*cornua\* from Pompeii, strongly suggesting that they were made by a single workshop. Very advanced technical skills (notably for tuning) are evident. The sample P20 studied here comes from the pavilion area of Cornu B1, Pompeii, 1st century CE, developed length of the Cornu 366 cm (Museo Archeologico Nazionale di Napoli, registered under #114261 in the January 1884 Pompeii excavation registry). See {Caussé, Mille, and Tansu 2020}. |
|  | **832** | Detail showing how the expansion of the iron armatures due to corrosion has generated a crack in the mirror. Jean-Baptiste Poultier (French, 1653–1719), Two Putti and a Girl Holding a Mirror, ca. 1685, cast by Aubry, Bonvallet, Schabol and Taubin in 1685–87, Paris, H. 145 cm (Musée National des châteaux de Versailles et de Trianon, France, inv. 1850.8925). See {Maral, Bourgarit, and Amarger 2014} for the metal composition of the cast. |
|  | **816** | The five types of casting defects commonly encountered on bronze sculpture. |
|  | **825** | Example of heavy losses in an incomplete high-tin bronze cast: the right hand is missing, and the left hand and attribute are full of defects. Bodhisattva Avalokitesvara, Gandhara, 3rd century CE, H. 37 cm (Musée National des arts asiatiques – Guimet, France, inv. MAO 12128). See forthcoming C2RMF Internal Report. |
|  | **549** | Annotated X-radiograph revealing extensive porosity. A large casting defect that extends partway through the surface of the figure’s proper left leg has been repaired with a set-in patch (yellow overlay). In many areas, porosity is contained within the wall (some are indicated in green). Jean-Antoine Houdon (French, 1741–1828), Diana, 1782, H. 208.3 cm (Huntington Art Museum, San Marino, California, inv. 27.186). See {Bassett and Scherf 2014}; {Bennett and Sargentson 2008}, 492–93. |
|  | **571** | Porosity on the surface of the bronze has been left unrepaired. Jean-Antoine Houdon (French, 1741–1828), Diana, 1782, H. 208.3 cm (Huntington Art Museum, San Marino, California, inv. 27.186). See {Bassett and Scherf 2014}; {Bennett and Sargentson 2008}, 492–93. |
|  | **875** | Example of defects on the surface near the base of a figure due to dross flowing into the mold with the melt. Andrew Lacey (British, b. 1969), hand-modeled copy in wax of Michelangelo, \*Slave\*, ca. 1516–19, H. 17.6 cm (Victoria and Albert Museum, inv. 4117-1854), used for private research. |
|  | **909** | Annotated X-radiograph reveals shrinkage porosity in the stomach and proper right hip (circled). Adriaen de Vries (Netherlandish, 1556–1626), Psyche Borne Aloft by Putti, 1590–92, H. 187 cm (Nationalmuseum, Stockholm, inv. NM Sk352). |
|  | **1058** | Bottom view of a statuette showing the 1 mm diameter hole (red arrow) after metal sampling (drillings) for elemental analysis by ICP-AES. Kubera/Jambhala, Java, ca. late 9th–early 10th century, H. 17 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3619). See {Mechling et al. 2018}. |
|  | **1096** | The many losses and worn appearance of the statuette are probably a result of ill-controlled electrolytic cleaning. Youth Holding an Oinochoe and Strainer, Greek, second quarter of the 5th century BCE, H. 11.8 cm (Harvard Art Museums / Arthur M. Sackler Museum, gift of Mrs. Edward Jackson Holmes, inv. 1952.20). |
|  | **829** | Back view of statuette showing numerous cracks. Saint John the Baptist, Italian (Venice), 16th century, H. 25 cm (Musée des beaux arts d’Angers, France, inv. 2003-1-192). See {C2RMF Internal Report 2018b}. |
|  | **111** | Detail of a cold shut on the proper right shoulder of the figure of Laocoön caused by premature cooling of the metal during the pour. Corrosion has accentuated the line where the cooling metal entered the mold from two different locations. Adriaen de Vries (Netherlandish, 1556–1626), Laocoön and His Sons, 1623, H. 169 cm (Nationalmuseum, Stockholm, inv. Drh Sk 68). |
|  | **1094** | The breakdown of the core shows the surface of the investment being lost and causing a granular encrustation inside the bronze. Experimental reconstruction of a torso by Andrew Lacey (British, b. 1969), 2012 (private collection). |
|  | **872** | “Orange-peel” effect on the bronze surface of the base. The size of the detail is ~50 mm. Siân Lewis (Welsh, b. 1964), \*Tree Tableaux II\*, cast by Andrew Lacey (British, b. 1969), 2017, H. 180 cm (artist’s collection). |
|  | **1106** | View of the cut-through section of a torso. During the metal pouring, the plaster core has floated upward, causing one side to be considerably thicker than the other. Andrew Lacey (British, b. 1969), maquette for \*Iconoclash\*, 2020, H. 13.5 cm (artist’s collection). |
|  | **1057** | Detail of inverse segregation on the figure’s cheek (one of the sons), appearing as a silvery color due to elevated surface tin content. Adriaen de Vries (Netherlandish, 1556–1626), Laocoön and His Sons, 1623, H. 169 cm (Nationalmuseum, Stockholm, inv. Drh Sk 68). See {Bassett 2008}. |
|  | **906** | The cast of the horse records large cracks that developed over time in the wax model, but are no longer visible on the sculpture, as the damage was later filled during restoration. Hilaire-Germain-Edgar Degas (French, 1834–1917), Horse Trotting, Feet Not Touching the Ground, ca. 1881–90, H. 23.5 (Harvard Art Museums / Fogg Museum, Bequest from the Collection of Maurice Wertheim, Class of 1906, inv. 1951.79). |
|  | **830** | Artist Andrew Lacey states: “The area between the breast or middle of the chest near the heart was moistened just prior to casting. This subjected the bronze to violent steam gassing, porosity, and a small vertical hole in the casting. It is highly organic in form and texture but leaves a mark that suggests weakness or wounding, or at least as a question in itself.” Personal communication to the authors, 2019. Andrew Lacey (British, b. 1969), \*Mud Ash Ochre\*, 2009, life-size torso (artist’s collection). |
|  | **519** | 360-degree general view (click on the image to spin) before restoration. Despite the high quality of the cast, several hundred repair patches have been observed. Eros of Agde, France, 1st century BCE, H. 63.5 cm (Musée de l’Ephèbe et d’Archéologie Sous-Marine de la Ville d’Agde, France, inv. 2888). See {Mille 2012}. |
|  | **515** | Diagram of the common types of repairs found on bronze sculpture. |
|  | **140** | Detail of mantle showing a pattern of cold-worked decorative striations applied over a rectangular patch that covers a casting defect. Germain Pilon (French, ca. 1525–1590), Kneeling Figure of Henri II, ca. 1567, H. 150 cm (Saint-Denis Basilica, France). See {Castelle 2016}. |
|  | **160** | Detail of a cast-on repair. Decorative lines were struck and/or engraved after the repair was cast in place. Modern copy of an Ife head, Nigeria, H. 32 cm (former private collection of Simon du Chastel, gift from Nathalie du Chastel to the Université Libre de Bruxelles). |
|  | **536** | Casting flaw with ancient patch repair. Lynx Incense Burner, Iran (Khorasan province), ca. 12th century, H. 28.5 cm (Musée du Louvre, inv. AA 19). See {Collinet and Bourgarit 2021}. |
|  | **551** | Jean-Antoine Houdon (French, 1741–1828), Diana, 1782, H. 208.3 cm (Huntington Art Museum, San Marino, California, inv. 27.186). See {Bassett and Scherf 2014}; {Bennett and Sargentson 2008}. |
|  | **224** | Monumental bronze finger recently shown to belong to the bronze statue of the Roman Emperor Constantine held at the Capitoline Museum. The outer edges of the patch repairs are clearly visible (yellow overlay). Monumental bronze finger, Rome, ca. 330 CE, H. 38 cm (Musée du Louvre, inv. Br78). See {Azéma, Descamps-Lequime, and Mille 2018}. |
|  | **527** | The process of setting in a patch to mask a superficial casting flaw: 1) casting flaw noted on the surface of the bronze (cross section); 2) the flaw is chiseled to create a geometric shape that is easily duplicated; an undercutting bevel is cut into the sides of the wall; 3) a metal patch is set into the flaw; 4) the patch is hammered and chased to fill the flaw and match the adjacent surface as much as possible; the repair is locked in place by the undercut of the bevel; 5) a similar process can be used to insert a plug to repair a flaw that extends through the entire thickness of the wall. |
|  | **534** | Diagram of a patch repair of a type seen on the statue of the Xanten Youth, Roman, last quarter of the 1st century BCE, H. 143 cm (Staatliche Museen zu Berlin, Antikensammlung, Neues Museum, inv. SK 4). 1) A copper alloy “granule” is positioned over a surface flaw; 2) a punch is used to force the granule into the flaw; and 3) the surface is further chased to conceal the flaw. After {Peltz 2011}, 127.1, fig. 12. |
|  | **230** | Detail of a casting defect in the right leg, showing where the patch repair has been lost. Jupiter, Roman, 1st century CE, H. 92 cm (Musée d’Art, Histoire et Archéologie d’Evreux, France, inv. FZ1520). See {Azéma et al. 2012}. |
|  | **35** | Detail of a tabernacle relief (H. 25 cm). The relief was cast with a large flaw. The figure of Christ was entirely remodeled in wax and cast separately in bronze. The cast repair was then inserted into the casting flaw and chased. Due to differences in the color of the alloy, the repair became visible while cleaning the surface (upper image). As seen at the back (lower image), once inserted in the primary cast, the newly cast repair was hammered to secure it. Note: the lower image has been rotated 180 degrees so that the two images are visually aligned. Girolamo (Italian, ca. 1510–1584/89) and Ludovico Lombardo (Italian, 1507/8–1575), Tabernacle, Chapel of the Holy Sacrament, Fermo Cathedral, Marche, Italy, by 1570–71, H. 230 cm. |
|  | **125** | Two types of repairs shown both inside and outside the cuirass that supports a figure. The blue overlay highlights two threaded plug repairs; the yellow overlay highlights a cast-on repair. Francesco Bordoni (Italian, ca. 1576–1654), Young Captive, 1618, H. 160 cm (Musée du Louvre, inv. MR 1668). See {Bourgarit, Bewer, and Bresc-Bautier 2014}. |
|  | **555** | The separately cast arm is attached with a Roman sleeve joint (red line). A large patch fills a flaw along the joint (blue overlay). A second patch is unrelated to the joint (green overlay). Threaded circular plugs (yellow overlays) help lock the arm joint and patches in place. Jean-Antoine Houdon (French, 1741–1828), Diana, 1782, H. 208.3 cm (Huntington Art Museum, San Marino, California, inv. 27.186). See {Bassett and Scherf 2014}; {Bennett and Sargentson 2008}, 492–93. |
|  | **101** | Detail of a cast-on repair in the center of a relief panel that has been set into the side of a Renaissance pedestal on which a Hellenistic bronze is mounted (yellow overlay). Also in yellow, the lower image shows the back side of the cast-on repair. The sprues, including a vent and a gate, were left in place and not removed (blue arrows). The repair was made with the relief face-down before being mounted to the pedestal. Idolino (Ephebe from Pesaro), ca. 30 BCE, base by the workshop of Girolamo (Italian, ca. 1510–1584/89), Aurelio and Ludovico (Italian, 1507/8–1575), Lombardo, perhaps after a drawing by Sebastiano Serlio (Italian, 1475–1544), 1530–1538/40, H. 148 cm (300 cm with base) (Museo Archeologico Nazionale, Florence, inv. 1637). |
|  | **566** | Annotated detail of a cast-on repair (left). The cast-on metal is surrounded by a thin gap due to shrinkage of the repair as it cooled. The annotated X-radiograph (right) reveals the gap around the repair and the excess metal cast into the interior of the hollow bronze as well as two tapering core pins. See **fig. 491** for a color photo of the backside of the horse. Aquamanile in the Form of a Lion, probably northern Germany, ca. 1200, H. 21.2 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.52). See {Dandridge 2006}. |
|  | **530** | Cast-on repair process: 1) casting flaw that extends through the wall of the bronze; 2) the edges of the flaw are cleaned up and core under the flawed area is partially excavated; 3) the flawed surface is modeled in wax; a pouring cup and vent are added; 4) the wax is invested; heat is applied locally until the wax melts out; 5) bronze is poured into the temporary mold; when cool, the investment is removed; 6) the pouring cup and vent are removed; the surface is chased to minimize the thin gap between the bulk metal and the cast-on repair caused due to shrinkage, and to unify the surface of the bronze. |
|  | **59** | Digital diagram illustrating a cast-on repair. 1) wax is applied to the loss and modeled in situ with a pouring gate; 2) investment is applied to cover the wax completely (for clarity, the investment in the sketch has been cut through to show the applied wax). Bonanno Pisano (Italian, active late 12th century), Porta di San Ranieri, Pisa Cathedral, Italy, ca. 1180, H. 470 cm. See {Morigi 1999}. |
|  | **62** | Surface detail (35 × 25 cm) showing a substantial cast-on repair. Circular holes cut along the borders of the gap allow the cast-on section to securely lock into place like a jigsaw. Pietro Tacca (Italian, 1577–1640), Fountain of the Marine Monsters, Florentine, 1626–37, H. 320 cm (Piazza Santissima Annunziata [northwest], Florence). |
|  | **631** | Detail of a cast-on repair on the back of the doe with dovetails that lock the repair in place (red overlay). The color variation between the repair and the primary casting (left) is due to the diverse microstructures and resulting corrosion of these sections. The corresponding gamma radiograph (right) helps to clarify the location of the different repairs (blue overlay) as well as the heavy porosity in the cast-on metal (dark spots). Barthélemy Prieur (French, ca. 1536–1611), Diana the Huntress, 1603, H. 200 cm (Musée national du château de Fontainebleau, France, inv. RF 261). See {Castelle 2016}. |
|  | **670** | Flow fusion welding repair. Each darkly outlined ovoid shape represents a fusion welding pour. The dark line is created at the melted zone between the fresh metal and the original bronze wall. It would not have been visible originally, but differences in the microstructure have led to corrosion variations. Statue of a Youth, ancient Rome, probably Asia Minor, ca. 140 CE, H. 142.6 cm (Toledo Museum of Art, purchased with funds from the Libbey Endowment, gift of Edward Rummond Libbey, inv. 1966.126). See {Mattusch 1996}. |
|  | **1083** | Illustration of a specially designed furnace used to repair a cracked bell by welding. From Vannoccio Biringuccio (Italian, 1480–1539), \*The Pirotechnia\*, 1540. See {Biringuccio [1540] 1942}, 276. |
|  | **419** | Annotated detail of an X-radiograph of the higher-density lead-based soldering metal that surrounds the set-in patch on the nymph’s right arm (arrows). Antonio Susini (Italian 1558–1624), Faun and Nymph, 1580–90, H. faun 48.2 cm, H. nymph 34.6 cm (Staatliche Kunstsammlungen, Grünes Gewölbe, Dresden, inv. IX 36). See {Bassett 2008}, 284. |
|  | **553** | Brazing metal (arrows) secures the separately cast back right leg and patch repair (yellow overlay). Brazing is confirmed by the elevated levels of zinc detected by XRF along the joint. Raised corrosion along the joints was probably caused by the remains of flux on the surface. Unidentified foundry, after Antoine Coysevox (French, 1640–1720), Fame, 1700–1710, H. 60.3 cm (Huntington Art Museum, San Marino, California, inv. 14.14). See {Bennett and Sargentson 2008}, 479. |
|  | **564** | Detail of a weld. In the photograph, the surface porosity indicates the location of the weld line on the carefully chased and polished surface; note that the color along the weld does not vary from that of the adjacent surfaces. The X-radiograph (right) reveals the uneven line of excess welding metal that remains on the interior along the join. Joan Mirò (Spanish, 1893–1983), \*Personnage\*, designed 1976, cast 1985, H. 213.4 cm (J. Paul Getty Museum, inv. 2005.116). |
|  | **517** | X-radiograph showing lead repairs filling surface flaws (overlay). A vertical bar behind the right shoulder was soldered in place as part of the support for Atlas to carry his burden (now missing). Workshop of Severo da Ravenna (Paduan, active 1496–1525/1538), Atlas, Italy, second quarter of the 16th century or later, H. 14 cm (Musée des beaux arts d’Angers, France, inv. 2003.1.198). See {C2RMF Internal Report 2018b}. |
|  | **281** | Restorations (likely made of a type of resin) on a bronze fluoresce are revealed under ultraviolet examination. Use the cursor to shift from full-daylight to full-UV image. The Worshipper of Larsa, Mesopotamia, 18th century BCE, H. 19.6 cm (Musée du Louvre, inv. AO15704). See {C2RMF Internal Report 2008b}. |
|  | **550** | Diagram of a simple core pin repair: 1) a ball of excess wax is applied adjacent to a core pin that has been inserted into the wax model (cross section); 2) the bronze is poured and the core pin is removed; 3) the resulting hole is filled by hammering the excess bronze into the void; 4) the metal that fills the hole is chased to match the surrounding surfaces. |
|  | **46** | Interior shot showing a seriously flawed area that has been repaired by inserting threaded plugs. Note the variation in their diameter. Giovanni Battista Bianco (Italian, d. 1657), after a design by Domenico Fiasella (Italian, 1589–1669), Virgin as Queen of Genoa, High Altar, San Lorenzo, Genoa, Italy, 1651, H. TK cm. |
|  | **226** | Comparison of X-radiography and gamma radiography of a monumental bronze finger—a fragment of the monumental statue of Emperor Constantin held at the Capitoline Museum. Different polygonal patch repairs are highlighted in red. The operating conditions for gamma radiography were: 3 × 2 mm 192 Ir source, 1 m source/object distance, 20 min. exposure, ERLM Dürr NDT H CR plate (resolution 50 µm), 0.1 mm Pb filtering before and after detector. Monumental bronze finger, Rome, ca. 330 CE, H. 38 cm (Musée du Louvre, inv. Br78). See **fig. 172** for a general view. See {Azéma, Descamps-Lequime, and Mille 2018}. |
|  | **361** | Annotated X-radiograph showing internal features of a sand cast: threaded repair plugs (blue overlay), core vents (yellow overlay), core support (orange overlay), and nuts that secure the horse to the base (green overlay). Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **562** | Annotated detail of an X-radiograph showing a cast-on repair in the seated figure’s right knee that shrank as it cooled, revealing the distinctive gap between the original wall of the bronze and the later cast-in metal. Francesco Bertos (Italian, 1678–1741), Group of Eleven Figures (Allegory of Autumn), ca. 1725, H. 79.5 cm (J. Paul Getty Museum, inv. 85.SB.74). |
|  | **839** | Threaded plugs are visible in the X-radiograph throughout the torso and in the raised proper left bicep (some marked with blue arrows). Attributed to Gian Lorenzo Bernini (Italian, 1598–1680), Neptune and Dolphin, 17th century (probably after 1623), H. 56 cm (J. Paul Getty Museum, inv. 94.SB.45). |
|  | **569** | Annotated digital X-radiograph showing extensive small rectangular patches (one example indicated with a yellow arrow) and a small number of circular threaded plugs (one indicated with a red arrow). Ferdinando Tacca (Italian, 1619–1686), Putto Holding a Shield, Florence, ca. 1650–55, H. 64.5 cm (J. Paul Getty Museum, inv. 85.SB.70). See {Fogelman and Fusco 2002}, 217. |
|  | **537** | Detail of X-radiograph revealing an internal metal cylinder added during restoration to join the body and tail. Lynx Incense Burner, Iran (Khorasan province), ca. 12th century, H. 28.5 cm (Musée du Louvre, inv. AA 19). See {Collinet and Bourgarit 2021}. |
|  | **557** | A casting flaw in a relatively hidden and difficult-to-reach location under the satyr’s sand-cast-bronze right leg (left image) has been repaired from below with sheet metal pinned under the base (right image). Formally attributed to Clodion (French 1738–1814), Nymph and Satyr, ca. 1850–75, H. 35.6 cm (Huntington Art Museum, San Marino, California, inv. 78.20.54). See {Bennett and Sargentson 2008}, 474–75. |
|  | **684** | Main assembly techniques encountered on bronze sculpture. |
|  | **1078** | Two ways of preparing the two parts to be assembled by flow fusion welding as witnessed on various antique large bronzes. Left side: the base metal is cut away to half its thickness to make a channel through which the molten bronze can run; right side: a space is left between the two parts to be joined and the welding metal is directly poured through this space. See {Azéma et al. 2011}. |
|  | **882** | A welding line along the joint of two separately cast parts of the base is visible on the surface due to variations in the patina (blue overlay). Henry Moore (British, 1898–1986), \*Seated Woman\*, designed 1958–59, cast 1975, H. 203.2 cm (J. Paul Getty Museum, inv. 2005.117.3). |
|  | **852** | Statue made of six separately cast pieces assembled by flow fusion welding (left). The welds appear as a sequence of adjacent ovals corresponding to a welding in basins (right). Captive Gaul, Gaul, last quarter of the 1st century BCE, H. 63 cm (Musée départemental Arles Antique [MDAA], France, inv. Rho.2007.06.1962). See {Azéma et al. 2013}. |
|  | **851** | Characteristic basin of a flow fusion weld defined at its outer edge by a discrete line of porosity (dotted red line). Horse of Neuvy-en-Sullias, France, 1st century BCE–1st century CE, H. 113 cm (Musée historique et archéologique de l’Orléanais, Orléans, France, inv. A6286). See {Mille 2007}. |
|  | **178** | Daylight photograph and X-radiograph of a detail of a right arm showing the brazing between the hand and the wrist (red line). The area was finished, removing any exterior signs of the joining method. Gilded Standing Divinity, Cambodia, Angkor, Siem Reap province, 11th century, H. 130.8 cm (Metropolitan Museum of Art, from the Collection of Walter H. and Leonor Annenberg, inv. 1988.355). |
|  | **853** | Detail of horse’s leg showing the location of the joint made by interlock casting (left). The joint mechanism is visualized in the diagram (right). The separately cast leg and body were assembled using a series of localized bronze pours (teal overlay). Iron shims (red overlay) and core material packed around the internal iron armature were used to contain each section of that pour. The joint was further secured by interlock casting, which entailed creating small openings on either side of the joint (teal squares) for the metal to key into. Andrea del Verrocchio (Italian, ca. 1425–1488) and Alessandro Leopardi (Italian, ca. 1465–1512), Equestrian Monument of Bartolomeo Colleoni, Venetian, 1479–96, over life size (Piazza SS Giovanni e Paolo, Venice). See general view of the monument, **fig. 100**. |
|  | **836** | Ritual vessel, China, Zhou dynasty, ca. 830 BCE, H. 36.5 cm (Freer Study Collection, Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. FSC-B-56). |
|  | **837** | Cross section of a vessel fragment that shows how the leg (secondary casting, green overlay), which was cast onto the body of a bronze vessel (lilac overlay), locked onto the primary casting mechanically. The reddish material in the center is the core preserved in the leg. Fragment of ritual vessel, China, Zhou dynasty, ca. 830 BC, H. 36.5 cm (Freer Study Collection, Department of Conservation and Scientific Research, Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. FSC-B-56). |
|  | **791** | The joints between the separately cast parts of this bronze chef-modèle are clearly visible. The group was designed to be disassembled and the sections used as patterns for sand molding. Jean-Baptiste Carpeaux (French, 1827–1875), chef-modèle of The Three Graces, 1872, H. 81.3 cm (Clark Art Institute, Williamstown, Massachusetts, inv. 1955.976). |
|  | **855** | X-radiograph showing the assembly of the arms by mortise and tenon (Roman joint). Lokeshvara, Khmer, late 12th century, H. 63 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 5960). See {Bourgarit et al. 2003}. |
|  | **868** | Gamma radiograph showing Roman joints in the arms of a figure. The type of joint used to attach the separately cast head cannot be determined in this radiograph. Gamma radiography was used due to the lack of available high-kV X-radiography. Thomas Ball (American, 1819–1911), \*Daniel Webster\*, 1853, sand cast probably after 1858, probably by the Ames Manufacturing Company, Chicopee, Massachusetts, H. 75.6 cm (Gilcrease Museum, Tulsa, inv. 0826.93). |
|  | **869** | Exterior detail of the figure’s straight arm showing the fine join line and circular outline of the pin or screw of a Roman joint. A joint in the neck is obscured by the collar. Thomas Ball (American, 1819–1911), \*Daniel Webster\*, 1853, sand cast probably after 1858, probably by the Ames Manufacturing Company, Chicopee, Massachusetts, H. 75.6 cm (Gilcrease Museum, Tulsa, inv. 0826.93). |
|  | **187** | Figures attached to a base using tangs and pins. In addition, a tang at the back of the gilt bronze Buddha figure has a hole for a pin to be inserted once the halo has been placed over the tang. Historical Buddha and Bodhisattvas, Buddhist altarpiece, northern China, Sui dynasty, 597 CE, H. 32.1 cm (Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, purchase—Margaret and George Halderman, and Museum Funds, gift of Charles Lang Freer, inv. F1914.21a–h). |
|  | **1082** | Annotated X-radiograph of Prajnaparamita and Lokeshvara showing the solid ring-shaped tangs cast with the statuettes to attach the figures to their base (arrows). Khmer Buddhist Triad, late 12th–early 13th century, H. 49.5 cm (National Museum of Cambodia, inv. Ga 2424). See {Bourgarit et al. 2003}. |
|  | **185** | The statue was cast in two sections—the figures with halo, and the base—which were joined by hammering the top edge of the base over the sculpture’s footplate to secure it. The red arrows in the overlay point to areas of overlap. Shiva Nataraja (Lord of the Dance), India, state of Tamil Nadu, Chola dynasty, ca. 990, H. 70.8 cm (Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, purchase—Margaret and George Halderman and Museum Funds, F2003.2). |
|  | **860** | On the underside of the base, two tangs secure the feet. The figure is a lost-wax cast and the base is sand cast. Augustus Saint-Gaudens (American, b. Ireland, 1848–1907), \*The Puritan\*, 1883–84, cast after 1899 at the Roman Bronze Works, New York, H. 78.1 cm (Gilcrease Museum, Tulsa, inv. 0826.114). |
|  | **857** | Three of the panther feet are set into recesses in the base and secured with pins (top), and detail showing tang securing one of the feet (bottom). Alexander Phimister Proctor (American, b. Canada, 1862–1950), \*Prowling Panther\*, 1891–92, sand cast 1905–12 at the John Williams Foundry, New York, H. 24.8 cm (Gilcrease Museum, Tulsa, inv. 0876.80). |
|  | **864** | Detail underneath the base shows tang attachments made with threaded rods that were cast integrally with the figure. Nuts are used to secure the base to the threaded rods. Gutzon Borglum (American, 1867–1941), \*The Fallen Warrior\*, ca. 1891, sand cast probably around that time in France, foundry unknown, H. 27.6 cm (Gilcrease Museum, Tulsa, inv. 0876.125). |
|  | **870** | Detail underneath side of a base shows screw attachments without Roman joints. Thomas Ball (American, 1819–1911), \*Henry Clay\*, 1858, sand cast after 1858, probably by the Ames Manufacturing Company, Chicopee, Massachusetts, H. 78.1 cm (Gilcrease Museum, Tulsa, inv. 0826.94). |
|  | **885** | Sketches showing how armature rods included in the construction of the model are used to mount the over-life-size equestrian figure of Louis XV to its pedestal. Left: overall view showing the armature rods extending beyond the hooves; right: cross section showing the internal armature in the legs (red overlay) and some of the external structural supports removed after casting (yellow overlay). {Mariette 1768}, ch. 4, plate IX, p. 56 (left), ch. 14, plate III, p. 160 (right), showing Edme Bouchardon (French, 1698–1762), Louis XV, Paris, cast in 1758 by Pierre Gor (French, 1720–1773), H. 520 cm. After {Desmas 2014}. |
|  | **1109** | Dan Kendall of New England Sculpture Service fabricated the stainless-steel armature while assembling the separately cast bronze parts of the monument (right). It was welded in to provide structural support and to anchor the work to its base. The detail inside the raven (left) seen here from the bottom was taken mid-process. Stefanie Rocknak (American, b. 1966), \*Poe Returning to Boston\*, 2014, H. 173 cm (City of Boston). |
|  | **175** | One of a pair of cloisonné enamel figures combining both cast sections (hands) and hammered sections (body and head) using mechanical methods for joining, namely bent tabs between head and body and rivets for the hands. Note that the enamel overlays are only on the hammered sections. Seated Figure, China, Qing dynasty, Qianlong period (1736–95), H. 88.3 cm (Metropolitan Museum of Art, gift of A. W. Bahr in memory of his wife, Helen Marion Bahr, 1954, inv. 54.124.2a–b.). |
|  | **883** | The separately cast cape secures to the proper right shoulder with a dovetail joint. The nearly identical alloys of the figure and the cape suggest that they were cast at the same time. After Willem Danielsz. van Tetrode (Dutch, ca. 1525–1580), Warrior on Horseback, 1562–65, H. 39.7 cm (J. Paul Getty Museum, inv. 85.SB.90). |
|  | **183** | Example of a figure mechanically attached to a separately cast base, which is closed and holds sacred relics. Six-Armed Hayagriva, China, Qing dynasty, second half of the 18th century, H. 16.5 cm (Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, The Alice S. Kandell Collection, inv. S2018.32). |
|  | **184** | Bottom view of a statuette showing the cover being held on the bottom of the base by chiseling burrs from the base of the sculpture over the copper cover. The remains of resins to aid in sealing the joint can also be seen around the outer edges of the cover. Six-Armed Hayagriva, China, Qing Dynasty, second half of the 18th century, H. 16.5 cm (Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, The Alice S. Kandell Collection, inv. S2018.32). |
|  | **1102** | The drapery of the bronze arm was cast in sections and assembled using a flow fusion weld (pink overlay) that is only visible from the interior. The welding appears as a chain of oval shapes. The arm was then joined to the drapery by welding (green overlay) with securing pins (blue overlay). Arm of a statue found in the Villa of Arconciel, Switzerland, end of the 1st–3rd century CE, greater than life size (Service Archéologique de l’Etat de Fribourg, Switzerland, inv. Arconciel/Es-Nés FR 85). See {Mille and Serneels 2012}. |
|  | **896** | Bright field photomicrograph of an etched polished cross section of the welded zone between the body and the neck of a bronze horse. Zone B corresponds to the filler metal (oval area of a basin), zone A to the neck of the horse (primary casting). The yellowish area between A and B is the melted zone (MZ) and the heat affected zone (HAZ), which consist of a mixture of the filler metal and the primary cast. This area is also marked by heavy porosity (black holes). Note that the elemental composition of the weld metal is strictly the same as that of the primary cast—that is, the neck (leaded bronze with 9.6 wt% Sn and 7.2 wt% Pb). Horse of Neuvy-en-Sullias, France, 1st century BCE–1st century CE, H. 113 cm (Musée historique et archéologique de l’Orléanais, Orléans, France, inv. A6286). See {Mille 2007}. |
|  | **1089** | Bright field photomicrograph of an etched cross section across a French 18th-century brazing joint between two cast brass elements. The section shows the typical large grains and dendritic structure of the two cast elements as well as the so-called Widmanstätten microstructure of the quickly cooled, high-zinc brass brazing metal (green overlay). Note that the two metals did melt into each other. Etched with a solution of 25% hydrochloric acid and 8% iron chloride in industrial methylated spirit. |
|  | **586** | Ultrasonic phased array applied to the study of the flow fusion welding of an antique large bronze. The C-scan represents the variations in thickness of the wall of bronze at the right leg-body junction (left). The profilometry of a welding basin (longitudinal and cross profiles) is shown (right). Captive Gaul, Gaul, last quarter of the 1st century BCE, H. 63 cm (Musée départemental Arles Antique [MDAA], France, inv. Rho.2007.06.1962). See {Azéma et al. 2013}. |
|  | **588** | Ultrasonic phased array applied to the study of the welding. Captive Gaul, Gaul, last quarter of the 1st century BCE, H. 63 cm (Musée départemental Arles Antique [MDAA], France, inv. Rho.2007.06.1962). See {Azéma et al. 2013}. |
|  | **762** | This slice from a computer tomography (CT) scan captured at the widest area of the neck shows a layer of metal separating the head from the body (see overlay). This is evidence that the head was cast on to an already-cast body by a localized lost-wax process. Excess metal dripped down a hollow channel along the vertical wooden armature in the torso. Elemental mapping by X-ray fluorescence (XRF) analysis revealed that the body is made of a different alloy than the head, confirming that the head was joined to the body at a separate stage. Seated Brahma, Cambodia, late 12th or early 13th century, H. 31.5 cm (Walters Art Museum, Baltimore, inv. 54.2734). See {Strahan 1998}. |
|  | **495** | Diagram of characteristic tool marks produced at various stages of the production of a bronze sculpture. |
|  | **153** | Tool marks made in the wax as seen under the base of a Tibetan divinity. Divinity of Tara blanche, Tibet, 17th century, H. 65 cm without base (Musée national des arts asiatiques – Guimet, Paris, inv. MA 12495). See {C2RMF Internal Report 2012}. |
|  | **3** | Detail of the figure’s back showing scattered clusters of rectangular-shaped matting marks disguising the repairs of casting defects (see overlay). Pierre Biard I (French, 1559–1609), Fame, ca. 1607, H. 134 cm (Musée du Louvre, inv. LP361). See {C2RMF Internal Report 2017}, 33054. |
|  | **110** | Two bronze cylinders (H. ~30 cm each) made by the Coubertin foundry, France, in the 1990s for the Musée du Louvre to show the different steps of casting and finishing. The as-cast state at the bottom of both cylinders is somewhat exaggerated. Note the triangular sprue and cylindrical vent in the left example, and their removal at right. |
|  | **532** | Marks of air tools and electric grinders on a cast bronze. |
|  | **75** | Bronze cylinder (the portion visible is ~12 cm high) demonstrating a range of chasing marks created using the chasing tools shown in **fig. 239**. From bottom to top: 1) raw, as-cast texture modeled in wax; at the center is the foundry mark struck with a steel punch (\*frappé\*) flanked by the punched letters “F” and “C”; 2) repetitive marks of a diamond-shaped matting tool with a smoothly textured tip (in French \*ciselet\*, and more specifically \*mat à bout lisse carré\*); 3) repetitive marks of a matting punch with a textured, granular tip (\*mat sablé moyen\*); 4) oblique marks of a veining punch with a coarse profile/contour (\*mat à tracer large\* or \*traçoir gros\*); 5) oblique marks of a veining punch with a refined, “sharpened” profile/contour (\*mat à tracer fin\* or \*traçoir fin\*); 6) polishing cloths of increasingly finer grit (200 to 1000) followed by electrical polishing wheel; 7) repetitive marks of a very fine veining punch (\*mat à tracer très fin\*); 8) oblique marks of a veining punch with a rounded profile/contour (\*mat à tracer large\* or \*traçoir gros\*); 9) repetitive marks of “dot” punch with a hemispherical, indented profile/contour (\*perloir\* or \*mat à perler\*); 10) repetitive marks of a matting punch with a finely textured tip (\*mat sablé fin\*); 11) repetitive marks of a “circle” punch with a rounded, circular perimeter and a recessed center profile/contour (\*perloir à touche\* or \*mat à perler\*). Bronze cylinder, 1990s, H. ~30 cm, made by the Coubertin foundry, France, for the Musée du Louvre, Département des sculptures. |
|  | **94** | Chasing tools belonging to Jean Dubos, Coubertin foundry, France, used notably to work the demonstration cylinder (**fig. 238**). From left to right: punch with smooth texture (in French \*ciselet\*, and more specifically \*mat à bout lisse carré\*); punch with a textured, granular surface (\*mat sablé moyen\*); tracer or scribe (\*mat à tracer fin or traçoir fin\*); veining tool (\*mat à tracer large\* or \*traçoir gros\*); fine-textured matting punch (\*mat sablé fin\*); and domed “dot” punch (\*perloir\* or \*mat à perler\*). |
|  | **154** | Tibetan divinity front view with a detail on the right showing the chased decoration in the fabric. Note the preparatory circle made with a compass (red lines) and the punch marks texturing the snake. Divinity of Tara blanche, Tibet, 17th century, H. 65 cm without base (Musée national des arts asiatiques – Guimet, Paris, inv. MA 12495). See {C2RMF Internal Report 2012}. |
|  | **191** | Reflectance transformation image (RTI) of the upper surface of the lotus of a lost-wax-cast statuette. This imaging technique allows examination of engraving marks made in the metal under variable lighting conditions. Statuette of Bodhisattva, Java, late 9th–early 10th century, H. 17 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3822). See {Mechling et al. 2018}. |
|  | **262** | The same punch marks with the same sequential strikes were found on two statues by Benvenuto Cellini (Italian, 1500–1571). The right image from the forehead of the bust of Bindo Altoviti, 1546–50, H. 105.5 cm (Isabella Stewart Gardner Museum, Boston, inv. S26e21) and in the left and middle images from Medusa’s neck on Perseus with the Head of Medusa, 1545–54, H. 320 cm (bronze group) (Loggia dei Lanzi, Piazza della Signoria, Florence). Micro-hardness tests were undertaken using a calibrated prism penetration durimeter, showing values very similar to that of a cold-worked copper surface. See [I.6](#I.6), note 17; {Morigi and Morigi 2004}. |
|  | **263** | Range of different cutting faces possible for engraving a surface: 1) wooden handles; 2) burin blade in a handle; 3) variety of shapes and sizes of cutting faces and burins. After {Untracht 1968}, 112. |
|  | **264** | Sampling of punches a chaser might use to cold work a metal surface. After {Untracht 1968}, 85. |
|  | **265** | Sampling of matting tool faces used in cold working a surface. After {Untracht 1968}, 96. |
|  | **889** | Detail showing peening on the back and arm of the warrior. This technique allows the light to bounce off the facets on the surface, creating a vibrancy when compared to a smooth, shiny surface reflection. Andrea Riccio (Italian ca. 1470–1532), Shouting Horseman, ca. 1510–15, H. 34.2 cm (Victoria and Albert Museum, Salting Bequest, inv. A.88:1-1910). See {Stone 1981}; {Stone 2008}; {Motture 2019}. |
|  | **14** | Detail of a flame handle with the marks of two different files visible across the surface. The red accretions within the incised lines are residues of a polishing compound utilized at some point in the object’s history. Aquamanile in the Form of a Lion, Nuremberg, Germany, ca. 1400, H. 31.9 cm (Metropolitan Museum of Art, The Cloisters Collection, 1994, inv. 1994.244). See {Dandridge 2006}. |
|  | **133** | Filing the surface of a contemporary Benin figure in a brass casting workshop, Igun Street, Benin City, Nigeria, 2002. |
|  | **1099** | Francesca Bewer chisels a metal flash off the leg of her experimental reproduction cast of Mars, 1989, after a model by Giambologna (Netherlandish, 1524–1608), ca. 1587, H. 40.5 cm. See {Bewer 1996b}. |
|  | **27** | Detail of experimental casting showing a scraper being pushed and pulled across the previously filed surface. The action creates a series of parallel, shallow depressions that are retained throughout the finishing process, creating a subtle modulation across the surface. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **1092** | Upon removal of the main feed on the side of the horse, a file and scraper were used to smooth the surface. The scraper produced chatter lines—here the short, parallel, vertical cuts—and the file the longer, undulating horizontal marks that reflect brightly against the surrounding darker, as-cast oxidized surface. Andrew Lacey (British, b. 1969), \*Pacing Horse\*, 2016, H. 23 cm, after-cast of bronze attributed to Gianfrancesco Susini (Italian, ca. 1585–1653) after a model by Giambologna (Italian, 1529–1608) (private collection). |
|  | **30** | Burnishing compresses the metal surface to reduce the distortion left by fine files or scrapers. This detail shows the haunch burnished with a highly polished and rounded antler tool. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **31** | Detail illustrating finishing of the surface with a shredded stick and a series of graded polishing compounds in a water or oil slurry. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **1** | Detail of head showing the crisp and faceted shape of the hair, partially reworked in the metal, and the use of a V-shaped graver to incise the eyebrows. Francesco Bordoni (Italian, 1580–1654), Young Captive, 1618, H. 160 cm (Musée du Louvre, inv. MR 1668). See {Bourgarit, Bewer, and Bresc-Bautier 2014}. |
|  | **132** | Chasing the surface of a copy of an Ife head in a brass casting workshop, Igun Street, Benin City, Nigeria, 2002. |
|  | **630** | Circular punch marks. Eagle Lectern, Hildesheim, Germany, ca. 1220, H. 57.5 cm (Dom Museum Hildesheim, Germany, inv. D 1984-2). |
|  | **156** | Detail of breast showing a lengthy inscription in the area across the diaphragm/solar plexus. The letters are quite irregular in shape and not deeply chased, which might testify to their cold working in the metal rather than in the wax. Bronze Statue of Hawtar’athat, Yemen, 1st millennium BCE, H. 140 cm (National Museum of Sana’a, Yemen, inv. YM 23206). See {Mille et al. 2010}; {Mille et al. 2012}. |
|  | **682** | This lost-wax statuette has an inscription on the base that is stamped into the metal. After a model by Gian Lorenzo Bernini (Italian, 1598–1680), Countess Matilda of Tuscany, ca. 1633–34, H. 40 cm (Harvard Art Museums / Fogg Museum, partial gift of Max Falk and partial purchase through the Director’s Acquisition Fund, 1998.1). See {Bewer 1999}. |
|  | **131** | Detail showing the number in the “Bronzes de la couronne” collection chased in the metal in the couch. Hermaphrodite, Florence, 1640–60, L. 41 cm (Musée National des châteaux de Versailles et de Trianon, France, inv. MV 7778, collection de la couronne n°30, on deposit at Musée du Louvre). |
|  | **71** | Inscription showing the initials of the sculptor (BP). Barthélemy Prieur (French, ca. 1536–1611), Diana the Huntress, 1603, H. 200 cm (Musée national du château de Fontainebleau, France, inv. RF 261). See {Castelle 2016}. |
|  | **1085** | Detail of the dancer showing the “cire perdue” stamp of the Hebrard foundry applied in the wax model, and edition number “16/D” engraved in the bronze. Edgar Degas (French, 1834–1917), \*Grande Arabesque, Third Time\*, ca. 1885–90, H. 40.6 cm (Harvard Art Museums / Fogg Museum, bequest from the Collection of Maurice Wertheim, Class of 1906, inv. 1951.78). |
|  | **67** | Inscription of the founder’s name chased into the cast. Antoine-Louis Barye (French, 1795–1875), cast by Lebeau (French, active 1850), Lion at the Porte des Lions, Palais du Louvre, Paris, commissioned 1847, H. 160 cm (Musée du Louvre, inv. LP 3483 bis). See {Lebon 2016}; <http://www.fontesdart.org/fontes-n100-elisabeth-lebon>. |
|  | **69** | Inscription chased on the base of the metal copy showing the inverted name of the artist. Copy of the Lion by Antoine-Louis Barye (French, 1795–1875), ordered in 1878, today at the Porte des Lions, Palais du Louvre, Paris, H. 160 cm (Musée du Louvre, no inv. number). See <http://www.fontesdart.org/fontes-n100-elisabeth-lebon/>. |
|  | **93** | Raised profile of the Bien Hoa foundry mark under the base of the Shiva (top of the image) indicates it was incised into the mold taken from the original before casting. Copy of Khmer Shiva, 20th century, H. 54 cm (Museum of Vietnamese History, Ho Chi Minh City, inv. BTLS.640). |
|  | **252** | Detail of the chased inscription. Roi Gardien, Korea, 12th century, H. 41 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 8153). See {C2RMF Internal Report 2004}. |
|  | **174** | Detail of left foot showing wear as a result of touching. Attributed to Arnolfo di Cambio (Italian, ca. 1240–ca. 1302/10), Saint Peter, ca. 1296, life size (Basilica of Saint Peter, Rome). See {Carruba 2006}. |
|  | **890** | Repeated touching has worn down the patina in certain areas, including the shoes. Jules Dalou (French, 1838–1902), Effigy on the Tomb of Victor Noir, 1890, life size (Père Lachaise Cemetery, Paris). |
|  | **87** | A section of the head and the trunk of a Ganesha, cut off by a modern tool. Khmer Ganesha, 13th century, H. 26 cm (National Museum of Cambodia, inv. Ga 5437). |
|  | **85** | Example of deconsecration of a Khmer divinity by cutting off the end of the attribute. Khmer Lokeshvara, late 12th–early 13th century, H. 42 cm (National Museum of Cambodia, inv. Ga 5340). |
|  | **888** | Effect of air abrasive (glass beads) on a copper-alloy surface bearing different cold-work marks: punches, chisels, stamps for marking editions and dates. The abraded surface (top half of image) is softened, and tool marks appear as if they were done in the wax rather than the metal. Didactic sheet by Andrew Lacey, May 2019. |
|  | **667** | Experimental simulation of engraving on wax (right) to demonstrate that the tool marks observed on the surface of the bronze bust of Antoninus Pius (left) were made in the wax model rather than in the cast bronze. The size of the area in the picture is about 2 × 2 cm. Giovanni Bandini (called Giovanni dell’Opera, Italian, 1540–1599), Bust of Roman Emperor Antoninus Pius, Urbino, TKdate, H. 68 cm (Museo Nazionale del Bargello, Florence, inv. 441B). See {Morigi 2018}. |
|  | **899** | Photomicrograph of punch marks in experimental cast produced during the 2004 ancient materials and technologies workshop “The Technical Analysis of Renaissance Bronze Casting” (AMTeC), Chatham Dockyard, UK. The same punch was used in the metal after casting (left), where it preserves its crisp outline, and in the wax before casting (right), where the distortion of the punch mark, the ridge of displaced malleable material along the edge, and the loss of crispness are all more common in marks made in the wax. |
|  | **169** | 3D model of a chiseled line generated by a digital microscope using automated focus stacking. The line, on a lost-wax statuette, is approximately 1 mm across. Click on the 3D image to turn it to visualize the altered V shape of the imprint, which demonstrates that the engraving in the metal was made by following a line already in the wax model. Statuette of Jambhala, central Java, first half of the 9th century, H. 28 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3814). See {Mechling et al. 2018}. |
|  | **141** | Francesco Bordoni (Italian, 1580–1654), Torchbearing Angel, 1613, H. 150 cm (Ecole Nationale Supérieure des Beaux Arts, Paris, inv. WB38). See {Bourgarit, Bewer, and Bresc-Bautier 2014}. |
|  | **142** | Detail of head whose surface has been severely weathered, destroying evidence of its cold working. Francesco Bordoni (Italian, 1580–1654), Torchbearing Angel, 1613, H. 150 cm (Ecole Nationale Supérieure des Beaux Arts, Paris, inv. WB38). See {Bourgarit, Bewer, and Bresc-Bautier 2014}. |
|  | **167** | Digital micrograph detail of the surface of a lost-wax cast statuette. Despite the evidence of wear and the corroded surface, digital microscopy proved efficient and necessary in revealing that the linear details were V-shaped and sharply defined, and thus indicative of having been made or reinforced by a graver. Statuette of Jambhala, central Java, first half of the 9th century, H. 28 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3814). See {Mechling et al. 2018}. |
|  | **22** | Detail showing the transition between the retained as-cast surface beneath the horse’s neck and the adjacent chased surface of the metal. Aquamanile in the Form of a Knight on Horseback, Germany (Lower Saxony?), ca. 1350, H. 45.2 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1409). See {Dandridge 2006}. |
|  | **12** | Features and textures of the bridle and eyes of the horse’s head were enhanced in the metal with chisel, engraver, and punch. Aquamanile in the Form of a Knight on Horseback, Lower Saxony, Germany (probably Hildesheim), ca. 1250, H. 37.3 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1492). See {Dandridge 2006}. |
|  | **168** | 3D reconstructed image of a chiseled line made in the metal (detail of left knee). Click on the 3D image to turn it to visualize the V shape of the imprint, which demonstrates the use of engraving. Statuette of Jambhala, central Java, first half of the 9th century, H. 28 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3814). See {Mechling et al. 2018}. |
|  | **11** | Detail from the handle that takes the form of the animal’s tail whose as-cast details have been aggressively reinforced with a V-shaped graver. With each strike of the graver, the tool jumps, creating the visible steps within the engraved line. Griffin Aquamanile, Nuremberg, Germany, 1425–50, H. 32 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1413). See {Dandridge 2006}. |
|  | **812** | Digital micrographs comparing the results of experimental chasing using a tracer on two different metals in two different metallurgical states. View of the chisel (left), the mark left in the as-cast tin-bronze and its dimensions (middle), and the mark in the laminated sheet of unalloyed electrolytic copper and dimensions (right). The copper sheet, having not been annealed, is much harder than the as-cast bronze, and consequently the mark is much shallower. Chasing by Dominique Robcis during the CAST:ING chiseling workshop, C2RMF, Paris, May 2017. |
|  | **813** | 3D model of a chisel mark in an as-cast tin-bronze. Model created with a digital microscope using automated focus stacking during the CAST:ING chasing workshop, C2RMF, Paris, May 2017. |
|  | **814** | 3D model of a chisel mark in an unalloyed electrolytic copper. Model created with a digital microscope using automated focus stacking during the CAST:ING chasing workshop, C2RMF, Paris, May 2017. |
|  | **797** | Comparison of an original gilt bronze mount (left) and an after-cast, nineteenth- or twentieth-century copy (right). The copy is more finely and “mechanically” chased in comparison to the original. The scale of the image is 9 cm from top to bottom. Attributed to André Charles Boulle (French, 1642–1732), pair of pedestals, ca. 1700 (J. Paul Getty Museum, inv. 88.DA.75.1–2). After {Heginbotham 2014}, fig. 1. |
|  | **235** | Digital microscopy detail of a punch mark (0.8 mm in diameter) on the lotus of a Buddha Vairocana. Note the smooth, compressed surface inflicted by the punch and the dimple of displaced metal around the edge. Buddha Vairocana, Indonesia, first half of the 10th century, H. 12 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 3475). See {Mechling et al. 2018}. |
|  | **236** | 3D model of a punch mark (0.8 mm in diameter) from the lotus of a Buddha Vairocana. The model was generated by a digital microscope using automated focus stacking. Note the imperfection in the sphere resulting from a defect on the face of the punching tool. Buddha Vairocana, Indonesia, first half of the 10th century, H. 12 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 3475). See {Mechling et al. 2018}. |
|  | **352** | Annotated detail of **fig. 288** showing three different phases of gilding as shown by the three different networks made by overlapping square gold leaves. Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See {Robcis et al. 2017}. |
|  | **350** | A Roman bronze gilded with gold leaf. Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See {Robcis et al. 2017}. |
|  | **336** | Woman applying gold leaf to Buddha statues as an act of worship, Shwedagon Pagoda, Yangon, Myanmar, 2018. Behind her in the blue basket are empty booklets of gold leaf. |
|  | **962** | Detail of the body showing the more prominent overlap of the gold leaf squares. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **348** | The surface of this cast-brass seated Buddha is mercury gilded except for the hair, which is pigmented blue. Seated Buddha, Central Tibet, 14th century, H. 45 cm (Freer Gallery of Art and Arthur M. Sackler Gallery, Smithsonian Institution, Washington, DC, purchase—Friends of the Freer and Sackler Galleries, S1997.28). |
|  | **892** | Bronze Statuette of a Quadruped (decorated with mercury gilding and silvering), China, Han dynasty, 202 BCE–220 CE, H. 7.5 cm (British Museum, reg. 1936,1118,257). See {La Niece 1990}. |
|  | **764** | Detail showing the eyes inlaid with silver, and the bridge of the nose, lips, and sideburns for evidence of where the mercury gilding dripped while being applied, or did not stay within intended boundaries. Note the typical Antico black patina and the particularly glossy surface. Pier Jacopo Alari Bonacolsi, known as Antico (Italian, ca. 1455–1528), Meleager, ca. 1484–90, H. 32.2 cm with original base (Victoria and Albert Museum, purchased with support from the Horn Bequest, the Bryan Bequest, and Art Fund, inv. A.27-1960). See {Stone 1981}; {Smith and Sturman 2011}; {Motture 2019}. |
|  | **893** | Detail showing brushstrokes from amalgam gilding application (detail size 4.4 × 2.9 cm). Lorenzo Ghiberti (Italian, ca. 1381–1455), Joseph panel in the \*Gates of Paradise\*, right door, H. 518 cm (design begun after 1425; installed 1452) (Museo dell’Opera del Duomo, Florence, inv. 2005/905). See {Bewer, Stone, and Sturman 2007}. |
|  | **757** | Bright field photomicrograph of an etched polished cross section of a modern mercury-amalgam gilded cast bronze. Typically the mercury gilding layer (top of image, ~5 µm thick) appears bright. Within the gilding layer it is common to see irregular lines that are residual outlines of the solidifying grains of gilding. The surface of the gilding is often smoother than seen in this modern example because extensive burnishing is carried out when a shiny finish is intended. The lower surface of the gilding layer can be uneven but well bonded to the substrate because heating causes some reaction of the gilding with the bronze. (Freer Department of Conservation and Scientific Research, Washington, DC, metallographic reference collection ME90069D). |
|  | **492** | Detail of the surface of a fake Han dynasty bronze showing the blistering electro-gilding. The width of the field of view is 1.5 cm. The blisters are tiny raised gold spots in the gilding that indicate the bronze was poorly cleaned to prepare for the gilding process. The visible red waxy deposits were applied by the forger to “age” the finish. Modern forgery of a Chinese Han period (202 BCE–220 CE) cast bronze in the form of a bear, H. 17.2 cm (British Museum, reg. no. 1947,0712.382). See {Jones 1990}, 257. |
|  | **247** | Detail showing foil gilding of face and hands using 0.1–0.2 mm gold foil (30–40% Ag) on an unalloyed copper cast. See also the aragonite in the left eye. The Worshipper of Larsa, Mesopotamia, 18th century BCE, H. 19.6 cm (Musée du Louvre, inv. AO15704). See {C2RMF Internal Report 2008b}. |
|  | **280** | Two vertical grooves in the neck (one is visible in the photograph) are filled with lead, possibly to hold gold leaf. Enthroned God, Mishrife, Syria, 17th century BCE, H. 17.2 cm (Musée du Louvre, inv. AO3992). See {C2RMF Internal Report 2009}. |
|  | **493** | Detail of the surface of an ancient Anatolian bronze showing mechanically applied foil gilding. The width of the field of view is 3.5 cm. Note that the foil masks the sharpness of the surface details on the bronze. Cast bronze, Uratu, northern Syria/Turkey, 7th–5th century BCE, H. 21 cm (British Museum, reg. no. 1880,1216.9). |
|  | **638** | Detail of the grooves on the neck and hairline (overlay) for the mechanical attachment of metal foils on the bronze head. Nike, Athens, 420–415 BCE, H. 20 cm (Ephorate of Antiquities of Athens City, Ancient Agora Museum [ASCSA, Agora Excavations B 30]). |
|  | **353** | Digital micrograph of a cross section showing several layers of gold due to regilding at the surface. Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See {Robcis et al. 2017}. |
|  | **354** | Backscattered electron micrograph of a polished cross section (ionic polishing) showing several layers of gold (white) due to regilding at the surface. Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See {Robcis et al. 2017}. |
|  | **417** | Ternary diagram for gold-silver-copper alloys indicating the color of different alloy compositions. |
|  | **418** | Decision tree for the preliminary investigation and characterization of plating by visual examination. |
|  | **325** | Decision chart for assessing the condition and characterizing an archaeological patina layer (in a museum laboratory setting). The protocol can be useful for the study of other surface layers as well, including metal plating and inlays. Three scenarios are covered: A) sampling is not possible; B) powder or flake samples are available; and C) cross section sampling is possible. The expected outcome of each approach is indicated at the bottom of the chart. |
|  | **301** | Research indicated that, although brightly polished when acquired (left), this sculpture was intended by the artist to have a thin brown patina. It was therefore allowed to darken by exposure to air for some years (middle). This appearance was still considered unacceptable, so repatination was deemed necessary to return it to its original appearance (right). Jean Arp (French German, 1886–1966), \*Human Concretion without Oval Bowl\*, 1933, cast 1961, H. 58.4 cm (San Francisco Museum of Modern Art, William L. Gerstle Collection, William L. Gerstle Fund purchase, inv. 62.2431). See {Hamilton 2018}. |
|  | **322** | Diagram showing the various factors involved in patina formation. |
|  | **335** | The well-adhered red and green patina formed naturally during centuries of burial. Partial cleaning has revealed the multicolored surface. Figure of a Lion, Anatolia or Syria, 1st millennium BCE, H. 18.7 cm (Metropolitan Museum of Art, purchase, Joseph Pulitzer Bequest, gift of Dr. Mortimer D. Sackler, Theresa Sackler and Family, and funds from various donors, inv. 2002.457 a–b). |
|  | **349** | Metallographic investigation of a cross section has shown that the dark-green patina on this bust formed naturally during burial and is of the type referred to as “noble patina” ({Gettens 1970}; {Robbiola and Hurtel 1997}). Heated glass-paste inlay is used to create solid and translucent colors within depressions or elevated chambers. Here, elementary chemical analysis indicates the eyes were produced using luxury glassmaking techniques, including colored glass ({Descamps-Lequime, Biron, and Langlois 2017}). Livia, Neuilly-le-Réal (Allier, France), 1st century CE, H. 21 cm; head H. 10 cm (Musée du Louvre, inv. Br 28). |
|  | **929** | The large cast-bronze head of a ruler displays typical corrosion found on bronzes from archaeological origin, with deep cracks formed by the advanced mineralization of the metal. Head of a Ruler, Iran or Mesopotamia, 2300–2000 BCE, H. 34.3 cm (Metropolitan Museum of Art, inv. 47.100.80). |
|  | **677** | Detail of face before restoration, showing the heavy corrosion due to long-term immersion in seawater (left) and after restoration (right). Electrolytic dechlorination was achieved via the total immersion of the figure in a basic solution over ninety days. Note the silver eye inlays revealed at right. Eros, Roman, 1st century BCE, H. 63.5 cm (Musée de l’Ephèbe et d’Archéologie Sous-Marine de la Ville d’Agde, France, inv. 2888). See {Mille 2012}. |
|  | **673** | Detail of the Vendôme Column before the 2015 restoration, showing how exposure to urban air pollution has caused corrosion. Various French sculptors, Vendôme Column, 1805–10, dismantled 1871, re-erected 1873–75, H. 44 m (Place Vendôme, Paris). See {Texier et al. 2016}. |
|  | **337** | Recently cast bronze replica busts, acid cleaned and awaiting patination at the Susse foundry outside Paris, 2012. |
|  | **668** | Details of four of the bronze plates from the Vendôme Column showing the influence of metal composition on the patina shade. All plates are made of leaded tin-bronze, except the repairs (zinc and tin-copper alloy). Tin content is steady, and lead controls the color: the higher the lead content, the higher the lead in the corrosion products, and the whiter the patina. In each plate, the different patina layers are revealed by polished cross sections observed under optical microscopy (center images) and scanning electron microscopy (SEM-BSE mode) (right images). The layers are, from bottom to top: metal, red cuprite, outer layer. The composition of the metal (XRF analyses) and of the patina (XRD) is indicated. Various French sculptors, Vendôme Column, 1805–10, dismantled 1871, re-erected 1873–75, H. 44 m (Place Vendôme, Paris). See {Texier et al. 2016}. |
|  | **291** | This statue was retrieved from the bottom of the ocean, heavily encrusted with marine deposits and corrosion layers. It is pictured here after mechanical cleaning, revealing a fairly smooth, continuous layer that is assumed to be close to the original surface. In the process, embedded copper chloride was also exposed, rendering the sculpture vulnerable to outbreaks of occasional active corrosion. For its long-term preservation, it is displayed and constantly monitored in an entirely desiccated gallery, which is continuously fed dry air. Statue of a Victorious Youth, Greek, 300–100 BCE, H. 151.5 cm (J. Paul Getty Museum, inv. 77.AB.30). |
|  | **300** | Detail of face, showing how storage near a furnace for many years caused damage in the form of dark spots to the patina from fumes. Aristide Maillol (French, 1861–1944), \*Standing Bather\*, 1899, H. 66 cm (Baltimore Museum of Art, gift of Blanche Adler, 1941.120). |
|  | **309** | Raised black islands on the surface of this badly corroded sculpture are due to aggressive urban air pollution over more than a century. A recent maintenance treatment of dark-tinted wax has minimized the surface color variation, although, as seen in the detail of the base with the foundry mark, the irregular surface texture caused by the corrosion is still quite apparent. Antoine-Louis Barye (French, 1795–1875), \*La Guerre\* (War), 1884 cast from 1855–56 model, H. 102 cm (Mount Vernon Place, Baltimore, given to the City of Baltimore by William Thompson Walters). |
|  | **1112** | The rough texture on the front of the right thigh is the trace of a coarse textile that was once in contact with the bronze surface and formed into a pseudomorph during the statue’s prolonged burial. Dionysos, Roman, Late Hellenistic, 1st century BCE–1st century CE, H. 135.8 cm (private collection, on loan to the Art Institute of Chicago). See {Mattusch 1996}, no. 23; {Ekserdjian 2012}, no. 44. |
|  | **292** | Bronze sculpture of horse and rider clearly made by a lost-wax casting process. The work exhibits a modern coating; the original surface appearance is unknown (and may never be known) due to repeated surface treatments it experienced after leaving Africa. Mounted Ruler, Edo Peoples, Benin, Nigeria, 16th century, L. 45.7 cm (Museum of Fine Arts, Boston, inv. L-G 7.12.2012). |
|  | **318** | The highly polished, unpatinated, oval bronze plane contrasts with the darker patinated surface of the rest of the sculpture. Henry Moore (British, 1898–1986), \*Two Piece Mirror Knife Edge\*, 1978, H. 47.6 cm (National Gallery of Art, Washington, DC, Adolph Caspar Miller Fund, gift of the Morris and Gwendolyn Cafritz Foundation, inv. 1978.13.1). |
|  | **297** | Malvina Hoffman chose different colors for skin and hair of \*Apache Man\* and worked closely with her chosen foundries to create realistic images of her subjects, as seen here. Malvina Hoffman (American, 1885–1966), \*Apache Man\*, 1934, H. 50.8 cm (Field Museum of Natural History, Chicago, inv. 337093). |
|  | **294** | After several trials in the early twentieth century to preserve the original dark-brown patina, this sculpture that stands in front of the MFA Boston was painted green at the artist’s behest to suggest even, natural corrosion. Cyrus Dallin (American, 1861–1944), \*Appeal to the Great Spirit\*, 1908, H. 309.9 cm (Museum of Fine Arts, Boston, inv. 13.380). See {Newman 2011}, 36. |
|  | **317** | Example of darker applied coating patina that has been worn through handling, revealing the lighter brown oxidized surface on the high spots. The Capitoline Wolf Suckling Romulus and Remus, Florentine, 15th century, H. 6 cm (National Gallery of Art, Washington, DC, Samuel H. Kress Collection, inv. 1957.14.8). |
|  | **1071** | The bright bottle-green patina is not a chemical patina, but rather a coating that was painted on. It is worn through on several high points and chipped off in a few areas. After Antoine-Louis Barye (French, 1795–1875), \*Panther of Tunis\*, ca. 1930–39, H. 13.3 (Harvard Art Museums / Fogg Museum, The Henry Dexter Sharpe Collection, inv. 1956.169). |
|  | **319** | Example of translucent reddish-gold patina typical of some Florentine Renaissance bronzes. Farnese Hercules, Florentine, ca. 1550–99, H. 56.8 cm (National Gallery of Art, Washington, DC, gift of Stanley Mortimer, inv. 1960.10.1). |
|  | **916** | Bronze cast with patina partly made with organic coating mixed with metallic flakes. Antoine-Louis Barye (French, 1795–1875), Dead Gazelle, modeled 1832, cast 1833–34 by Honoré Gonon (French, 1780–1850), H. 7.6 cm (Walters Art Museum, Baltimore, inv. 27.96). |
|  | **918** | Photomicrograph detail showing metallic flakes in the organic patina. Antoine-Louis Barye (French, 1795–1875), Dead Gazelle, modeled 1832, cast 1833–34 by Honoré Gonon (French, 1780–1850), H. 7.6 cm (Walters Art Museum, Baltimore, inv. 27.96). |
|  | **759** | This piece has lived outdoors for more than three centuries as part of the Neptune Fountain at Drottningholm Palace in Sweden. Its natural patina is varied due to different types of exposure. It ranges from an attractive, glossy, warm brown to a more matte and streaky green and black. Adriaen de Vries (Netherlandish, 1556–1626), Naiad (Ceres), 1615–18, H. 142 cm (Nationalmuseum, Stockholm, inv. NMDrh.Sk50). See {Scholten 1998}, 218. |
|  | **334** | Detail of leg showing darker rectangular repairs. It is likely that the numerous repaired casting flaws were originally intentionally hidden by a dark or opaque coating. These repairs are now visible due to exposure to the weather and loss of original coating. Simon Mazière (French, 1649–1722), \*Un Amour tenant un oiseau et deux enfants\*, ca. 1685, cast by Aubry, Bonvalet, Schabol, and Taubin 1686–90, H. 161 cm (Water Parterre, Musée National des châteaux de Versailles et de Trianon, France, inv. 1850.8931) See {Maral, Bourgarit, and Amarger 2014}. |
|  | **305** | Detail of leg, showing core material from inside the sculpture that migrated to the surface of this porous bronze when the weather was particularly wet. The surface has been covered with a tinted wax coating to reduce porosity, water incursion, and irregularities in the surface color. Mercury, 19th-century Italian reproduction of a bronze from Herculaneum, H. 131 cm (Baltimore Museum of Art, gift of the City of Baltimore, Department of Recreation and Parks, inv. 1948.46). |
|  | **306** | Core material from inside has migrated to the surface of the chin in this porous bronze during wet years, causing green corrosion. The left image shows it before treatment. After removal of the green corrosion by power washing, the raw pink bronze was revealed because the corrosion had destroyed the brown patina (right). More core material has since migrated (white areas) from the interior. Jo Mora (American, b. Uruguay, 1876–1947), \*Indian Maiden\*, 1928, cast by the California Art Bronze Foundry, Los Angeles, H. 182.8 cm (Woolaroc Museum and Wildlife Preserve, Bartlesville, Oklahoma, inv. SCT-47). |
|  | **891** | Machine oil was applied in a misguided attempt to spruce this work up, and years later, disfiguring black patches have emerged on the surface of the patina due to interaction with the oil. Alexander Phimister Proctor (American, b. Canada, 1862–1950), \*Q-Street Buffalo\*, 1912, sand cast in 1912–13 in Brussels at Verbeyst Foundry, H. 33.7 cm (Gilcrease Museum, Tulsa, inv. 08.840). |
|  | **1072** | Fingerprint on polished brass caused by a reaction of the metal with salts and acids on human skin. |
|  | **758** | Exposure to a harsh urban environment has altered any original patina into a mottled, discolored, and somewhat powdery corroded surface that is very different from the original appearance. William Henry Rinehart (American, 1825–1874), Endymion, 1874, L. 182.9 cm (marker for the sculptor’s own grave at Greenmount Cemetery, Baltimore). |
|  | **293** | The application of libation and holy pigment to a copper alloy sculpture forms multilayered encrustations. Divinity in the Courtyard of the Golden Temple, Patan, Nepal, date and dimensions unknown. |
|  | **320** | Bronze fountain sculpture that developed a natural patina over time from water runoff in an outdoor environment. Follower of Giovanni Bologna (called Giambologna, Flemish, based in Florence, 1529–1608), Venus and Cupid, Italian, 16th century, H. 124.5 cm (National Gallery of Art, Washington, DC, gift of John and Henrietta Goelet, in memory of Thomas Goelet, and Patrons’ Permanent Fund, inv. 1991.242.1). |
|  | **295** | Detail of a thin bronze plate showing “bronze disease”—light-green-colored eruptions of copper chlorides. Breastplate with Relief Decoration of a Four-Horse Chariot, southern Italy, ca. 480 BCE, L. 107 cm (J. Paul Getty Museum, inv. 83.AC.7.3). |
|  | **323** | Set of examination and testing protocols for the characterization of a patina layer both for sculpture that is not likely to have been buried and for archaeological bronzes. For the latter, these are very general notes; the question of burial might be more nuanced than presented here and can lead to much more complex situations (e.g., archaeological bronzes may be subsequently coated). See **fig. 305** for more details on the relevant techniques of analysis. |
|  | **645** | Two patinated copper-alloy plates (red and black) showing the influence of surface texture on the perception of color. For each plate (~20 × 20 cm), the upper half of the surface has been left as-cast, while the lower half has been polished before patination. Samples provided to the C2RMF by the Coubertin foundry, France, in the late 1990s. |
|  | **193** | Schematic representation of general types of inlay (A–I) and overlay (J–L). A) cavity with undercuts and chased line with undercut; B) cast cavity with secondary receiver holes to reinforce the primary element with pins; C) cast depressions left in the surface to receive inlays; D) complex preformed inlay inserted into mold and cast in place; E) formed metal inlay in chased recesses with undercuts; F) pre-shaped abutting inlay elements in single chamber; G) translucent inlay backed by metallic foil; H) hammered metal foil on roughened surface; I) through-hole cavity with insertion from reverse; J) cloisonné-type chamber surface mount for gemstones; K) cloisonné-type chambers on surface with multicolored design; L) cloissoné-type chambers on surface with multicolored design. |
|  | **347** | Detail of left foot showing silver inlay on the inscription. Piombino Apollo, Greek, 120–100 BCE, H. 115 cm (Musée du Louvre, inv. Br. 2). See {Descamps-Lequime and Mille 2017}. |
|  | **269** | Digital photomicrograph showing areas of preserved silver wire and of a larger silver-plate inlay in hammered brass that has been chased to draw the face (top of image). Some of the silver has been lost, revealing the champlevé preparation for the larger silver-plate inlay (white overlay at center and bottom). A number of the incised lines would also have been inlaid with silver wire. Ewer, Afghanistan (Herat), ca. 1200, H. 39 cm (Musée du Louvre, inv. OA 5548). See {Collinet and Bourgarit 2021}. |
|  | **202** | Stylized gold and silver inlays depict snakes and birds on a figure that was probably used as a tray support. Figure of a Leaping Feline, China, Eastern Zhou dynasty, 4th–3rd century BCE, H. 23 cm (British Museum, 1883, donated by Sir Augustus Wollaston Franks, inv. 1020.5). |
|  | **282** | Detail showing inlaid eyes (silver) and lips (copper). Jupiter, Roman, 1st century CE, H. 92 cm (Musée d’Art, Histoire et Archéologie d’Evreux, France, inv. 5404). See {Azéma et al. 2012}. |
|  | **256** | Eyespots made of copper inlays as shown by PIXE analysis (black on the photograph, probably due to corrosion) in a leaded tin bronze. Panther, Gaul, 1st century CE, H. 50 cm (Musée des Antiquités Nationales, Saint-Germain-en-Laye, France, inv. 79767). See {C2RMF Internal Report 1997}. |
|  | **585** | Annotated detail of copper-alloy inlays. The lips and blood drips are inlaid with a reddish high-copper alloy (blue and orange annotations). A lead-rich overlay simulates a swollen cheek contusion of a different color (purple overlay). Boxer at Rest, Greek, Hellenistic period, late 4th–2nd century BCE, H. 128 cm (Museo Nazionale Romano di Palazzo Massimo, Rome, inv. 1055). See {Alessandri et al. 2013}. |
|  | **274** | Lost-wax cast of a head of a Bodhisattva showing the brass and copper bead decoration in the tiara. The brass beads belong to the primary cast (both contain 21 wt% Zn), whereas the copper beads were shaped from a wire and overlaid on the cast. Bodhisattva, Tibet, 11th–13th century, H. 34.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 6273). See {C2RMF Internal Report 1998}. |
|  | **678** | Detail of the face of the Reclining Vishnu. Because of heavy corrosion, the inlays are no longer visible, but only known through surface analysis: copper has been detected in the lips, and lead in the moustache and beard. Composition of the eye inlays is unknown. Note texture in the eyebrows of material probably used to attach the inlay. Reclining Vishnu, West Mebon (Khmer), 12th century, L. 220 cm (National Museum of Cambodia, inv. Ga 5387). See {CAST:ING 2018}. |
|  | **212** | Buddhist deity represented in cast bronze with silver and copper inlays to enhance the eyes, and a stone set in the \*usnisa\* (top). The inset stone emphasizes the symbolism of the attainment of reliance on a spiritual guide. Seated Statue of Dhyanibuddha Akshobhya, Tibet, 12th–13th century, H. 32 cm (British Museum, Trustees of the British Museum, inv. 1981,1109.1). |
|  | **523** | Detail of the chest of an ancient Egyptian statuette showing different color inlays: yellow, pink, and white-gray. PIXE analysis identified four different gold alloys: pure gold, electrum (gold and silver in equal proportions), gold with 25 wt% Cu, and gold with 34 wt% Cu and 6 wt% Ag. Karomama, Egyptian, Twenty-Second Dynasty, first quarter of the 1st millennium BCE, H. 59.5 cm (Musée du Louvre, inv. N500). See {Delange, Meyohas, and Aucouturier 2005}. |
|  | **194** | Eye inlays held in place within folded copper sheets, often with eyelashes as shown here (bronze/copper lashes, marble sclera, glass frit iris, quartz and obsidian pupil). Originally, the eyes would have been inserted into a cast-through cavity. Eye inlays, Greek, 5th century BCE or later, H. 3.8 cm (Metropolitan Museum of Art, purchase, Mr. and Mrs. Lewis B. Cullman Gift and Norbert Schimmel Bequest, inv. 1991.11.3a–b). |
|  | **210** | Gilt statuette overlaid and bejeweled with a range of semiprecious stones (possibly lapis lazuli, turquoise). Note the cavities and loss of stones in the proper right armband. Durga as Slayer of the Buffalo Demon Mahishasura, Nepal, 14th–15th century, H. 22.2 cm (Metropolitan Museum of Art, gift of Alice and Nasli M. Heeramaneck, 1986, inv. 1986.498). |
|  | **808** | Detail of cloak. The royal arms are created from lapis lazuli and silver, with the heraldry representing the king’s various territories. Pompeo Leoni (Italian, 1533–1608) and others, Cenotaph of Philip II of Spain, 1597–1600, H. 170–190 cm (Basilica of the Royal Monastery of San Lorenzo of El Escorial, Spain, inv. 10034776). See {Arias 2012}. |
|  | **253** | Detail of overlaid stones and gems. Divinity of Tara blanche, Tibet, 17th century, H. 65 cm without base (Musée National des arts asiatiques – Guimet, France, inv. MA 12495). See {C2RMF Internal Report 2012}. |
|  | **596** | Detail of front inlay. Previously thought to be enamel, under microscopic examination by Michael Wagner and Rainer Richter (Grünes Gewölbe) all the blue inlays were shown to be blue glass with oil-bound gold pigment on top. Filarete (Antonio di Pietro Averlino, Italian, ca. 1400–1469), Marcus Aurelius, 1440–45, H. 38 cm (Grünes Gewölbe, Dresden, inv. H4 155/037). Personal communication with Claudia Kryza-Gersch, 2018. |
|  | **535** | Detail of turquoise-blue glazed fritware inlay in the empty eye socket of a high-lead-brass incense burner. Lynx Incense Burner, Iran (Khorasan province), ca. 12th century, H. 28.5 cm (Musée du Louvre, inv. AA 19). See {Collinet and Bourgarit 2021}. |
|  | **200** | Cast bronze with gold appliqués and traces of powdered mineral inlay. Lidded square wine jar (\*fanghu\*), China, Late Eastern Zhou dynasty or Middle Warring States period, ca. 481–300 BCE, H. 48.3 cm (Los Angeles County Museum of Art, gift of Mr. and Mrs. Lidow, inv. M.76.109a–b). |
|  | **413** | An early example of a hollow cast bronze (weight 15 kg); the leaded copper-arsenic jacket is filled with lead. The jacket is decorated with seashell inlays depicting a hunting frieze in which a leopard attacks an ibex. The scene is repeated twice, separated by stylized flies. High energy X-ray tomography at 8 MeV was conducted at the linear accelerator at the Laboratoire d’électronique des technologies de l’information (CEA-Leti). Leopard Weight, Pakistan, end 4th–early 3rd millennium BCE, H. 16.7 cm (Mission archéologique française au Makran, Shahi-Tump, inv. 298II402PO644). See {Mille, Besenval, and Bourgarit 2004}; {Mille 2017}. |
|  | **222** | Wooden mask with inlays and attachments made of raffia, fur, and pigment. Inlays and attachments to wood and ivory masks and sculptures may provide clues as to lost elements in bronze masks and statues. Mask, Democratic Republic of the Congo, Kasai River region (Leele peoples), 19th–20th century, H. 51.4 cm (Metropolitan Museum of Art, the Michael C. Rockefeller Memorial Collection, gift of Mr. and Mrs. Gustave Schindler, 1967, inv. 1978.412.540). |
|  | **223** | Lines of holes run between the lobes of the ears and across the upper lip of a brass Ife head. Based on ethnographic parallels, these may possibly be for the attachment of added elements. Red paint is used to add color to feathers; tubular beads and rosettes and traces of black paint appear on incised elements of the crown. Ife head, Yoruba, probably 14th–early 15th century, H. 35 cm (British Museum, inv. Af1939,34.1). |
|  | **286** | Detail of an engraved bronze plate showing red pigment inside the letters, identified as cinnabar by XRD and PIXE. Plate, 1st–3rd century CE, 34 × 50 cm (Musée d’Art, Histoire et Archéologie d’Evreux, France, inv. 4891). See {Azéma et al. 2012}. |
|  | **211** | Bronze figure mercury gilded with overlaid stones and painted pigments. Buddhist Deity Vajradhara in Union with His Consort Prajnaparamita, probably Chinese or Tibetan, 1403–24, H. 28.6 cm (Metropolitan Museum of Art, Robert Lehman Collection, inv. 1975.1.1442). |
|  | **340** | Top: reproduction wax; bottom: detail showing copper lips, which were precast inlays, manufactured and set into the wax model prior to bronze casting. This method is suitable for more complex inlay shapes and profiles. Riace Bronze Statue A, Greek, ca. 460 BCE, H. 198 cm (Museo Nazionale della Magna Grecia, Reggio Calabria, Italy). See {Bertelli et al. 2013}. |
|  | **287** | Left: remains of soldering used to attach inlays on the fragment of an unidentified large bronze statue, Roman, 1st–3rd century CE, H. 21 cm (Musée d’Art, Histoire et Archéologie d’Evreux, France, inv. 4860). See {Azéma et al. 2012}. Right: similar inlays of similar sizes have been observed on numerous antique large bronzes, as can be seen on the cloth (left hand), Statue of the Emperor Augustus, Roman, 29 BCE–14 CE, life size (National Archaeological Museum of Athens, inv. X23322). |
|  | **763** | The Mensa Isiaca bronze table (probably an altartop) with Isis presented at center is inlaid with multipart, alloyed-metal inlays to create a series of friezes in imitation of much earlier Egyptian dynastic scenes. The alloys may have been further patinated for color effect. Mensa Isiaca, Roman, 1st century CE, H. 75.5 cm (Turin Museo Egizio, Italy, inv. 715). |
|  | **344** | Some basic tools for measuring statuettes: a) dial vernier caliper; b) outside (or external) calipers; c) T-squares; d) cloth tape measure. |
|  | **815** | Annotated X-radiograph showing technical features observed on the front surface. Click on the legend to reveal or mask the different overlays (refer to **fig. 467** for mapping of evidence visible on the reverse). Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE., max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **1069** | Poster titled “The Hephaistos database. A tool for the technological study of large bronze statues from Classical Antiquity,” presented at the XVIIIth congress on ancient bronzes in Zurich, 2013. See {Descamps-Lequime and Mille 2017}. |
|  | **1107** | An image of a sculpture 150 cm high, photographed at a resolution of 2048 × 1536 pixels, will not resolve details at the mm scale (see inset at top right). Macro photography is necessary to resolve fine features such as tool marks and signatures (see inset at bottom right). Statue of a Victorious Youth, Greek, 300–100 BCE, H. 151.5 cm (J. Paul Getty Museum, Villa Collection, inv. 77.AB.30). |
|  | **612** | Conservators examining the inside of the base of Venus with a video endoscope, which presents the images live on screen. Francesco Primaticcio (Italian, 1504–1570), Venus, 1542, H. 192 cm (Musée national du château de Fontainebleau, France, inv. MR 3277). See {Castelle 2016}. |
|  | **643** | The principle of reflectance transformation imaging (RTI). |
|  | **1111** | Color measurements on bronze sculpture typically utilize the CIELAB color space, where colors are defined by the three variables (L\*, a\*, and b\*) representing light-dark, red-green, and yellow-blue, respectively. |
|  | **644** | Principle of photogrammetry. |
|  | **664** | The main steps to design a resin model of a sculpture using photogrammetry: 1–2) digital photography of the original sculpture is undertaken at several angles to cover the whole object; 3) a digital model made of a dense cloud of points is made via reconstruction software; 4) the digital model is meshed and cleaned; 5) a 3D model is printed (here in resin) using the digital model; 6) details are added as well as painting. |
|  | **666** | 3D model of the new stainless steel mount for the bust (left), and back view of the bust once mounted (right). The mount was created using a 3D model designed using photogrammetry. Giovanni Bandini (called Giovanni dell’Opera, Italian, 1540–1599), Bust of Roman Emperor Antoninus Pius, Urbino, TKdate, H. 68 cm (Museo Nazionale del Bargello, Florence, inv. 441B). See {Morigi 2018}. |
|  | **702** | Digital 3D structured light scan. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **661** | 3D structured light scan. Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br 37 [NIII65]). See **fig. 288**. |
|  | **911** | Two 3D models of different versions of a terra-cotta sculpture were made using a structured light scanner. By overlaying the scans, it is clear that while the torsos are closely aligned, the hands, hair, and lapels are misaligned, suggesting possible joint locations for the separately mold-made parts. Albert-Ernest Carrier-Belleuse (French, 1824–1887), Model for a Monument to Alexandre Dumas, 1885, H. 76 cm (Musée Carnavalet, Paris, inv. S1893; Musée Alexandre Dumas, Villers-Cotterêts, France, inv. 91.2.54). See {Carré 2005}. |
|  | **1088** | Interactive 3D laser scan of the reassembled surviving sections of the dolphin relief produced by P. Mora and L. Espinasse and presented on the Archéovision website. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **771** | A reconstruction of the frieze based on 3D laser scans. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **960** | Detail of the virtual 3D reconstruction of the frieze showing what may have been its original dichromatic appearance. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **370** | Schematic diagram of an X-radiography setup. |
|  | **373** | The influence of the thickness of copper samples (upper image) on the attenuation of X-rays (lower image). The thicker the sample, the greater the attenuation, and the lighter the resulting radiograph. The thickness is indicated by the diameter of the hole: 2 / 2.5 / 3.2 / 4 / 5 / 6.3 mm. |
|  | **371** | The four different parameters controlling the attenuation of X-rays in matter: the wavelength of the X-ray beam λ (the attenuation factor α is proportional to λ3); the atomic number Z of the element the beam passes through (α is proportional to Z4); the mass density ρ of the matter the beam passes through (α is proportional to ρ); and the thickness η of the object to be radiographed (the variation of intensity of the transmitted X-ray ΔI/I is proportional to the difference of thickness Δη). The thinner the arrow below the object (the cube), the greater the attenuation of X-rays. See {CETIM 2017}. |
|  | **657** | Assembled gamma radiographs. Ponce Jacquiot (French, 1515–1571), Prudence, Henri II and Catherine of Medici Funerary Monument, 1567, H. 190 cm (Saint-Denis Basilica, France) See {Castelle 2016}. |
|  | **659** | Assembled gamma radiographs. Francesco Primaticcio (Italian, 1504–1570), Venus, 1542, H. 192 cm (Musée national du château de Fontainebleau, France, inv. MR 3277). See {Castelle 2016}. |
|  | **368** | Schematic diagram of an electron emission radiography setup. |
|  | **367** | Electron emission radiographs from different metals showing that only the atomic number of the element controls the image density: the lightest sample is aluminum, the darkest is lead, and the thickness of the sample has no impact. Operating conditions are indicated at the bottom of the image (source – distance object to detector – filter – voltage/intensity/exposure time). |
|  | **369** | Comparison of electron emission radiography (right) versus X-ray radiography (middle) as seen on the Plaque à l’aurige, 4th century CE, H. 17 cm (Musée du Louvre, inv. Br3447). Daylight photography on the left. The electron emission image nicely reveals the inlays of gold and silver in the copper substrate. See {Robcis et al. 2014}. |
|  | **634** | X-radiographic sequence. Jupiter (or Neptune?), Bavay (Nord, France), 1st century CE, H. 26.4 cm (Musée Archéologique de Bavay, France, inv. 1969 Br 15 / Biévelet 10). See {Mille 2019a}. |
|  | **376** | The influence of geometry on image quality for X-radiography: 1–2) the greater the distance between source and object, the sharper the image; 3–4) the closer the detector to the object, the sharper the image; 5–6) non-rectilinear arrangements can produce geometric distortion of the image; 7–8) the smaller the X-ray source (focal spot), the sharper the image. |
|  | **381** | Head of a polychrome stone sculpture (calcareous) in visible-light photography and in X-radiography. The blurring of the radiograph is due to X-ray scattering generated by the object itself. King Childebert, Abbaye Saint Germain des Prés, Paris, 1239–44, total H. 1.9 m (Musée du Louvre, inv. ML 93). |
|  | **378** | Because of the thickness of the metal wall and the relatively high density of the leaded copper alloy, high energy (400kv, 4 mA) and a thick filter (10 mm copper) were necessary for X-radiography. The other operating conditions were: 10 min. exposure, 3 m source-to-object distance, MX125PB film. Eros and Psyché, Roman, 1st century BCE–1st century CE, H. 72 cm (Musée du Louvre, inv. Br 4105/MND 1035). See {C2RMF Internal Report 2015a}. |
|  | **377** | X-radiograph of a bronze hare or aardvark. Due to the relative thinness of the bronze walls (<2 mm), relatively low voltage (250 kV) proved sufficient for X-radiography. Other operating conditions (C2RMF): 2mA, 6 minute exposure, 2 m source-to-object distance, 4 mm copper filtering, M100PB film. Bronze Hare or Aardvark, Egypt, 11th century CE, L. 63 cm (Musée du Louvre, inv. OA 6675). |
|  | **391** | Antoine-Louis Barye (French, 1795–1875), Theseus and the Centaur Bienor, cast by Eugène Gonon (1814–1892) in 1877, H. 1.3 m (Musée du Louvre, inv. RF 3882). See {C2RMF Internal Report 2016b}. |
|  | **379** | X-radiograph of a pair of \*couvre seins\* (breastplates). Contrast optimization in order to reveal hammering marks was obtained by discarding the X-ray beam filters. Other operating conditions were: 80kV, 4mA, 10 min. exposure, 1.5 m source-to-object distance, MX125PB film. Pair of \*couvre seins\*, Iran, early 2nd millennium BCE, 12 cm diameter (Musée du Louvre, inv. Sb 3055 a–b). |
|  | **640** | Typical setup of computerized tomography (CT), either with a line detector (top) or a flat panel detector (bottom). |
|  | **394** | X-ray tomographic views of a bronze statuette. Software allows detailed measurements to be made of any feature. Jupiter (or Neptune?), Bavay (Nord, France), 1st century CE, H. 26.4 cm (Musée Archéologique de Bavay, France, inv. 1969 Br 15 / Biévelet 10). See {Mille 2019a}. |
|  | **395** | Segmentation of X-ray tomographic reconstructions can digitally isolate and highlight individual features, making them easier to visualize. Jupiter (or Neptune?), Bavay (Nord, France), 1st century CE, H. 26.4 cm (Musée Archéologique de Bavay, France, inv. 1969 Br 15 / Biévelet 10). See {Mille 2019a}. |
|  | **443** | X-radiograph of frontal view. Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **1049** | Annotated neutron radiograph of frontal view, showing more clearly than the X-radiograph (**fig. 400**) the contours of the sealing material (red overlay) and some of the consecration offerings (purple, red, and green overlays). For an even better visualization of the consecration offerings (in another statuette), refer to the tomographic images in **figures 403** and **404**. Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **642** | Mass attenuation coefficients for thermal neutrons as a function of atomic number of elements. A higher coefficient means the element is more opaque to neutrons. |
|  | **449** | Neutron tomography. Vairocana, Java, first half of the 10th century, H. 15.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 18290). See {Mechling et al. 2018}. |
|  | **1050** | Neutron tomography (in negative for better visualization). Click on the image to spin. Vairocana, Java, first half of the 10th century, H. 15.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 18290). See {Mechling et al. 2018}. |
|  | **607** | Ponce Jacquiot (French, 1515–1571), Prudence, Henri II and Catherine of Medici Funerary Monument, 1567, H. 190 cm (Saint-Denis Basilica, France). See {Castelle 2016}. |
|  | **608** | Ponce Jacquiot (French, 1515–1571), Temperance, Henri II and Catherine of Medici Funerary Monument, 1567, H. 187 cm (Saint-Denis Basilica, France). See {Castelle 2016}. |
|  | **342** | Measuring the height of a statuette using a combination of wooden framing squares, a T-square, and a measuring tape. Note that the metal edge of the T-square has been covered in tape to protect the surface of the bronze. Giuseppe Piamontini (Italian, 1663–1744), Bacchus and Ariadne, ca. 1700–1744, H. 40 cm, H. on base 47.9 cm (J. Paul Getty Museum, inv. 83.SB.333). |
|  | **343** | Measuring the width and depth of a statuette (viewed from above) by placing it in a virtual box. The gridded support on which the figure rests simplifies the determination of the box’s perpendicular lines. Camille Claudel (French, 1864–1943), Torso of a Crouching Woman, model ca. 1884–85, cast by 1913, H. 35 cm (J. Paul Getty Museum, inv. 2018.32). |
|  | **341** | Measuring the depth of a statuette using a combination of wooden framing squares and a measuring tape. Giuseppe Piamontini (Italian, 1663–1744), Bacchus and Ariadne, ca. 1700–1744, H. 40 cm, H. on base 47.9 cm (J. Paul Getty Museum, inv. 83.SB.333). |
|  | **627** | The measurements of a sculpture will vary significantly depending on the position one choses to take them in—choices that are particularly challenging when there is no obvious primary view, or when an object is fragmentary. For the sake of argument, Francesca Bewer positioned the rearing horse, flawed with its front legs missing, in several ways and measured the width and length, projecting the farthest points onto gridded paper, to show the variations. The uppermost gridded sketch reflects measurements taken with the horse in alignment with the paper (red lines correspond to the horse upright on its hind legs, the blue ones with it posed on all fours). The bottom two images show measuring done with the horse at an angle, first upright (lines in blue), then lowered (lines in red). The height, of course, will vary in relation to the position. Andrew Lacey (British, b. 1969), equine study demonstration model, 2004, H. TK cm (private collection), cast by the artist in 2004 for experimental purposes at AMTeC (Ancient materials and technologies) Renaissance bronze workshop, Chatham Dockyard, UK. |
|  | **405** | Plaster molding of the edge of a fragment from a monumental Reclining Vishnu to test whether it is part of the left arm of the bust. Left to right, top to bottom: a plastic film is laid on the bronze surface; an imprint of the edge is made using clay; the resulting clay mold is filled with plaster; view of the plaster imprint; test of the plaster imprint against the left shoulder. Reclining Vishnu, West Mebon (Khmer), 12th century, L. 220 cm (National Museum of Cambodia, inv. Ga 5387). See {CAST:ING 2018}. |
|  | **760** | Example of geometric morphometric analysis on Iron Age iron lances. The various shapes of lances are superimposed using a specific protocol called generalized procrustes analysis (upper image). In the lower image, each point represents a normalized measure, for a given lance, at a predefined location or “landmark.” See {Birch and Martinón-Torres 2019}, fig. 9. |
|  | **977** | A representation of accuracy and precision. The top-left image shows a target hit with a high degree of accuracy but low precision. The top-right image shows the target hit with high precision but low accuracy. At bottom left, the target is hit with neither precision nor accuracy, and at bottom right the target is hit with both accuracy and precision. |
|  | **1070** | 2D chemical mapping by XRF of the right profile of a bronze animal head showing gold inlay in the eye (green); silver teeth and silver inlay in the cheek (blue); and copper in the cast bronze substrate (red). Statuette of a Dog or a Wolf, Bavay (Nord, France), 1st century CE, H. 6.8 cm (Musée Archéologique de Bavay, France, inv. 1969 Br 23/ in. Biévelet 20). See {Mille 2019a}, 182–85; {Laval, Calligaro, and Mille 2019}. |
|  | **48** | Mapping of cracks, defects, and cast-on metal on the heavily repaired right ankle of the Perseus monument was undertaken before restoration using an Eddy current probe (red and white lines) and a microwave probe (yellow lines and dots). Eddy currents detect all areas of discontinuity in a metallic surface. White lines are the outline of the cast-on repair, which was difficult to see and includes adjacent circular plugs that help lock the patch to the metallic wall. Microwaves detect air bubbles (yellow dots) or areas of discontinuity even under the surface. The round area at top right represents a sprue and was visible under raking light. Benvenuto Cellini (Italian, 1500–1571), Perseus with the Head of Medusa, 1545–54, H. 320 cm (bronze group); 199 cm (base, modern) (Loggia dei Lanzi, Piazza della Signoria, Florence). Morigi Restauratori, unpublished conservation report. |
|  | **1059** | Drilling a sample from a statuette. In this case, a 1 mm diameter steel bit was used, drilling to a depth of 1 cm into the base. The metal drillings are collected on clean paper and carefully sorted under magnification to avoid any contamination by dust and/or corrosion products. Five-Headed and Ten-Armed Śiva, Angkor, 13th century, H. 38.5 cm (National Museum of Cambodia, inv. Ga 2778). |
|  | **592** | Sampling for metallographic study of welding. Horse of Neuvy-en-Sullias, France, 1st century BCE–1st century CE, H. 113 cm (Musée historique et archéologique de l’Orléanais, Orléans, France, inv. A6286). See {Mille 2007}. |
|  | **593** | Sampling an antique bronze horse using a diamond wheel. The cross section was taken at the body-neck junction in order to study the assembly process (fusion welding). A mobile bronze mane (removed here) hides the sampling location. Horse of Neuvy-en-Sullias, France, 1st century BCE–1st century CE, H. 113 cm (Musée historique et archéologique de l’Orléanais, Orléans, France, inv. A6286). See {Mille 2007}. |
|  | **457** | Bright field photomicrograph of an etched polished cross section of the welding zone of an experimental sample. See the dendritic microstructure of the primary cast. The outlines of dendrites appear colored; the interdendritic space is filled with eutectoïd phase alfa + delta (in blue). Sample E26, binary bronze CuSn10. See {Azéma et al. 2012}; {Azéma and Mille 2013a}. |
|  | **461** | Bright field photomicrograph of an etched polished cross section of the welding zone of an experimental sample. See the dendritic microstructure and small grains due to recrystallization in the heat-affected zone (HAZ) generated by flow fusion welding. The outlines of dendrites appear brown; the interdendritic space is filled with eutectoïd phase alfa + delta (in blue). Sample E66, binary bronze CuSn10. See {Azéma et al. 2012}; {Azéma and Mille 2013a}. |
|  | **456** | Backscattered electron micrograph of a polished cross section showing the dendritic microstructure of the primary cast. The outlines of dendrites appears dark gray; the interdendritic space is filled with phase alfa + delta (eutectoïd composition) and various inclusions (light gray) as well as nodules of lead (white oval shape). Large bronze fragment from the hoard of Evreux, France, 1st century CE, L. 14 cm (Musée d’Evreux, France, inv. 4864). See {Azéma et al. 2012}; {Azéma and Mille 2013a}. |
|  | **458** | Backscattered electron micrograph of a polished cross section showing the dendritic microstructure of the primary cast of an experimental sample aimed to investigate fusion welding (E26, binary bronze CuSn10). The outlines of dendrites appear dark gray; the interdendritic space is filled with phase alfa + delta (eutectoïd composition) (light gray). See {Azéma et al. 2017}. |
|  | **460** | Backscattered electron micrograph of a polished cross section showing the dendritic microstructure and grains of the primary cast of an experimental sample aimed to investigate fusion welding (E54, binary bronze CuSn10). The outlines of dendrites appear dark gray; the interdendritic space is filled with phase alfa + delta (eutectoïd composition) (light gray). See {Azéma et al. 2012}; {Azéma and Mille 2013a}. |
|  | **978** | Backscattered electron micrograph showing a corroded tin layer on the surface of cast brass with a dendritic structure. |
|  | **242** | Photomicrograph under plane-polarized transmitted light of a thin section of a casting core. Francesco Primaticcio (Italian, 1504–1570), Laocoön and His Sons, 1542, H. 191 cm (Musée national du château de Fontainebleau, France, inv. MR 3290). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **243** | Photomicrograph under cross-polarized transmitted light of a thin section of a casting core. Francesco Primaticcio (Italian, 1504–1570), Laocoön and His Sons, 1542, H. 191 cm (Musée national du château de Fontainebleau, France, inv. MR 3290). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **572** | Photomicrograph under cross-polarized transmitted light of a thin section of the casting core showing its characteristic grain size distribution (see **fig. 525**,core recipe 1). Martin Lefort (French, dates unknown), Justice, 1571, H. 128 cm (Musée du Louvre, inv. MR1682). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **573** | Photomicrograph under cross-polarized transmitted light of a thin section of the casting core showing its characteristic grain size distribution (see **fig. 525,** core recipe 2). Ponce Jacquiot (French, 1515–1571), Temperance, Henri II and Catherine of Medici Funerary Monument, 1567, H. 187 cm (Saint-Denis Basilica, France). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **244** | Photomicrograph using cathodoluminescence of a thin section of a casting core. Francesco Primaticcio (Italian, 1504–1570), Laocoön and His Sons, 1542, H. 191 cm (Musée national du château de Fontainebleau, France, inv. MR 3290). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **245** | Photomicrograph under cross-polarized transmitted light of a thin section of a casting core. The different grains are sorted according to their gray level (green outlines) and characterized (shape, dimensions) using image analysis software. Francesco Primaticcio (Italian, 1504–1570), Laocoön and His Sons, 1542, H. 191 cm (Musée national du château de Fontainebleau, France, inv. MR 3290). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **241** | Example of a casting core sample taken from underneath. Francesco Primaticcio (Italian, 1504–1570), Sleeping Ariadne, 1542, L. 240 cm (Musée national du château de Fontainebleau, France, inv. MR 3284). See {Castelle 2016}. |
|  | **240** | Sampling of casting core in process. Barthélémy Prieur (French, ca. 1536–1611), Diana the Huntress, 1603, H. 200 cm (Musée du Louvre - Fontainebleau Castle, inv. RF261). See {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **637** | General age range of items, including bronze sculpture, that can be dated by radiocarbon and luminescence techniques. |
|  | **623** | Diagram of the cycle of radiocarbon formation and decay in organic materials that underlies the principles of dating. |
|  | **1087** | Two examples of radiocarbon dating results generated using OxCal 4.4 software (see {Bronk Ramsey 2009}). The radiocarbon determination is represented, along with its uncertainty, as the red curve along the vertical axis; the narrower the curve, the more precise was the instrumental measurement. The blue band represents the IntCal20 calibration curve, which accounts for minor variability in carbon-14 concentration in the atmosphere over time (see {Reimer et al. 2020}). The gray curves along the horizontal axis (calibrated date) represent the probability that the sample actually originated at any given time; the higher the curve, the greater the probability that the date below is correct. The brackets below the gray curves show the time period that is 95.4% certain to contain the true age. Depending on the precision of the measurement and the shape of the calibration curve, a radiocarbon analysis can yield results of varying precision, and can even yield results with more than one possible date range. |
|  | **625** | Sampling process on an iron armature from a bronze. Palanquin Hook in the Shape of a Monkey, late 12th–early 13th century, H. 17 cm (National Museum of Cambodia, inv. Ga 4745). See {Leroy et al. 2021}. |
|  | **675** | Design of wax models for castability tests: A) setup of the sprues and vents (4 mm and 6 mm in diameter); B) preparation of the wax wire (1 mm, 2 mm, and 3 mm in diameter); C) soldering of the wax wire; D) the wax models once completed; E) setup of the metal mold; F) molds once completed; G) molding using refractory plaster; G) molds in the stove for dewaxing and baking; H) molds ready for metal pouring. Experiments carried out at Coubertin foundry, France, 2015. See {Mille 2017}. |
|  | **676** | Castability tests devised by the C2RMF were carried out at the Coubertin foundry, France, in 2015. The distance that the molten metal travels in channels of different diameters is used as measure of its castability. A) copper and copper alloy rods of specific compositions were melted in preparation for the test; B) hollow channels of different diameters were made in refractory molds using wires of different gauges, and the baked molds were transferred to the furnace; C) the melt temperature was measured prior to pouring; D) the alloy was poured into the molds; E) each mold was weighed post-pour to gauge the quantity of metal; F) each mold was then radiographed at the C2RMF to assess how far the metal had traveled. See {Mille 2017}. |
|  | **498** | Brass-making experimental simulation. View of the furnace used for the laboratory experiments at C2RMF (left) and the large furnace used during field experiments at Barsy, Belgium (right). See {Bourgarit 2015}; {Thomas and Bourgarit 2018}. |
|  | **932** | Front view of the first head. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **934** | Front view of the second head. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **936** | Front view of the body. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **938** | Front view of the upper fragment of the body. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **940** | Front view of a fragment of the upper tail. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **942** | Front view of a fragment of the tip of the upper tail. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **944** | Front view of a fragment of the lower tail. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **931** | The Museum of Vienne’s former presentation of the Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). From {Boucher 1964}. |
|  | **946** | Former attempt at a reconstruction of the composition of the surviving fragments. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. From {Boucher 1964}. |
|  | **933** | Rear view of the first head. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **935** | Rear view of the second head. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **937** | Rear view of the body. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **939** | Rear view of the upper fragment of the body. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **941** | Rear view of a fragment of the upper tail. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **943** | Rear view of a fragment of the tip of the upper tail. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **945** | Rear view of a fragment of the lower tail. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technical evidence, refer to **fig. 367**. |
|  | **947** | Assembly of the front views of the two heads showing that these two elements used to be connected (red line). Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **948** | Detail of the connection of the first head to the two body fragments, also showing the neat cutout at the top, possibly the place for a rider (arrows). Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **949** | The front view of the two heads reveals a neat square hole between them (overlay), the result of the impact of a pile driver used in 1839 during the building of the Rhone riverbanks. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **950** | The new presentation of the frieze. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **952** | 3D model of the rear surface of the surviving fragments showing the assembly of the different parts. The red bands represent flow-fusion welding zones. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **774** | Rear surface of a body fragment of a dolphin showing a long weld joint and numerous rivet heads used to secure the largest polygonal repair patches on the front side. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). See technical sketch, **fig. 367**. |
|  | **954** | Detail of an X-radiograph of a dolphin’s body in which the denser welding zone appears as a brighter white area in the center, the rivets show up as small white donuts with darker centers, and porosity appears as black flecks. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). For a description of all visible technological evidence, refer to **figs. 367, 467**. |
|  | **953** | 3D model of the rear surface of the surviving fragments showing the welding zones in red, and in the foreground, the metal reservoir in the form of a basin where the welding metal was poured in. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **957** | Detail of an X-radiograph of the first dolphin head, in which the extensive porosity appears as dark spots of various sizes and densities. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **958** | Detail of the front view of the body fragment showing the location of a lost repair polygonal patch that was fastened by rivets (now rivet holes, see green spots). Numerous patches and rivet heads (orange spots) are also visible at this location (see also **fig. 466**). Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **959** | Detail of the back view of the body fragment showing the flow fusion weld (red overlay). Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **956** | Annotated X-radiograph showing the technical features observed on the reverse. Click on the legend to reveal or mask the different overlays (see **fig. 367** for mapping of evidence visible on the front). Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **961** | The body fragment was cleaned mechanically using an ultrasonic scalpel. Great Dolphins of Vienne, Roman period, Vienne, France, 2nd century CE, max L. 260 cm (Musée des beaux-arts et d’archéologie de Vienne, France, inv. R.1998.2.43). |
|  | **1012** | Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). |
|  | **1013** | Aquamanile in the Form of Samson and the Lion, northern Europe (?), possibly Germany, ca. 1380–1400, H. 34.1 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1412). |
|  | **15** | Aquamanile in the Form of a Lion, Nuremberg, Germany, ca. 1400, H. 31.9 cm (Metropolitan Museum of Art, The Cloisters Collection, 1994, inv. 1994.244). |
|  | **1014** | Partially fabricated wax model for an experimental casting. Additional wax is applied to the wax sheet in the reproduction for the modeling of the lion’s mane. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **1015** | Modeling the clay core for an experimental casting. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Barnet and Dandridge 2006}. |
|  | **1026** | Completed core for an experimental casting. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). |
|  | **1016** | Backscattered electron micrograph of a polished cross section of a core sample. The large rounded grains are quartz and potassium feldspars, with the former being darker gray. The dark splintery shapes at the top left are pieces of organic material. Aquamanile in the Form of a Lion, probably northern Germany, ca. 1200, H. 21.2 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.52). See {Dandridge 2006}. |
|  | **1027** | A wax sheet is cut and applied over the core with seams secured with a hot spatula. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). |
|  | **1017** | Radiograph. Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **1018** | Radiograph confirming the use of an even layer of wax to form the lion’s body and mane, as well as the location of the circular core plugs. Aquamanile in the Form of a Lion, Nuremberg, Germany, ca. 1400, H. 31.9 cm (Metropolitan Museum of Art, The Cloisters Collection, 1994, inv. 1994.244). |
|  | **1019** | Detail. Aquamanile in the Form of a Falconer on Horseback, northern Germany, 13th century, H. 34.7 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.55). See {Dandridge 2006}. |
|  | **1020** | Detail from a radiograph of an aquamanile, showing the print for the original armature extending up through the center of the rider’s torso and visible as a slightly less dense, darker channel within retained core material. Aquamanile in the Form of a Falconer on Horseback, northern Germany, 13th century, H. 34.7 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.55). See {Dandridge 2006}. |
|  | **1021** | Detail. Aquamanile in the Form of Samson and the Lion, northern Europe (?), possibly Germany, ca. 1380–1400, H. 34.1 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1412). See {Dandridge 2006}. |
|  | **1022** | Detail from radiograph of an aquamanile showing that the form of Samson’s core extends into his legs and arms, and that the lion’s mane was fully modeled in the core. Aquamanile in the Form of Samson and the Lion, northern Europe (?), possibly Germany, ca. 1380–1400, H. 34.1 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1412). See {Dandridge 2006}. |
|  | **1023** | Fully sprued wax model for an experimental casting. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). |
|  | **1024** | Detail from an aquamanile illustrating the rod-shaped strut extending out of the chest and supporting the falconer’s right arm, as well as the exaggerated length of the glove flap on his opposite arm, allowing for the circular flow of metal during the pour. Aquamanile in the Form of a Falconer on Horseback, northern Germany, 13th century, H. 34.7 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.55). See {Dandridge 2006}. |
|  | **1028** | Detail showing a core pin fabricated from a folded piece of copper sheet. Aquamanile in the Form of a Lion, probably northern Germany, ca. 1200, H. 21.2 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.52). See {Dandridge 2006}. |
|  | **1029** | Detail showing both iron and copper core pins in the lion’s head. Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **1030** | Interior detail showing the protruding tip of a surviving core pin that was fused to the surrounding metal. Aquamanile in the Form of a Lion, Germany (Lower Saxony), late 13th–early 14th century, H. 21.0 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1490). See {Dandridge 2006}. |
|  | **1031** | Detail of circular disc inserted as a core plug and secured with solder. Aquamanile in the Form of a Lion, Nuremberg, Germany, ca. 1400, H. 31.9 cm (Metropolitan Museum of Art, The Cloisters Collection, 1994, inv. 1994.244). See {Dandridge 2006}. |
|  | **1046** | This scatter plot of alloys used in the study group analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) illustrates an increased concentration of zinc in aquamanilia produced in Nuremberg at the beginning of the 15th century. See {Dandridge 2006}. |
|  | **1034** | Detail showing the cast-in repair on the top of the animal’s head (see red overlay). Aquamanile in the Form of a Rooster, Germany (Lower Saxony), 13th century, H. 25.2 cm (Metropolitan Museum of Art, The Cloisters Collection, 1989, inv. 1989.292). See {Barnet and Dandridge 2006}. |
|  | **1035** | Detail showing the cast-in repairs across the animal’s rump, also visible in the radiograph in **fig. 180**. Aquamanile in the Form of a Lion, probably northern Germany, ca. 1200, H. 21.2 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.52). See {Dandridge 2006}. |
|  | **1036** | Detail of side showing the location of the core plug illustrated in **fig. 488**. Aquamanile in the Form of a Lion, Nuremberg, Germany, ca. 1400, H. 31.9 cm (Metropolitan Museum of Art, The Cloisters Collection, 1994, inv. 1994.244). See {Barnet and Dandridge 2006}. |
|  | **1038** | Detail illustrating the use of a spade drill to clarify the iris and a V-shaped graver to delineate the edges of the feathers, other details, and the punch work around the snout of a dragon. The faint parallel marks across the neck are indications of the use of a scraper to help smooth the surface. Aquamanile in the Form of a Dragon, northern Germany, ca. 1200, H. 21.2 cm (Metropolitan Museum of Art, The Cloisters Collection, 1947, inv. 47.101.51). See {Barnet and Dandridge 2006}. |
|  | **1039** | Detail of head illustrating where a V-shaped graver defined the lion’s mane, a flat chisel refined the ear, and punch marks made whisker holes in the cheek. Aquamanile in the Form of a Lion, Germany (Lower Saxony), late 13th–early 14th century, H. 26.1 cm (Metropolitan Museum of Art, The Friedsam Collection, bequest of Michaelk Friedsam, 1931, inv. 32.100.198). See {Barnet and Dandridge 2006}. |
|  | **1040** | Detail from centaur’s chest showing the use of a scorper to define U-shaped designs with the series of steps within each cut corresponding to the strike of the mallet or hammer. Aquamanile in the Form of a Crowned Centaur Fighting a Dragon, possibly Hildesheim, Lower Saxony, Germany, 1200–1225, H. 36.5 cm (Metropolitan Museum of Art, Rogers Fund, 1910, inv. 10.37.2). See {Dandridge 2006}. |
|  | **1041** | Detail showing double strike of a circle and dot punch used to ornament the belt. Aquamanile in the Form of Phyllis and Aristotle, southern Netherlands, late 14th or early 15th century, H. 32.5 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1416). See {Barnet and Dandridge 2006}. |
|  | **1042** | Detail showing inlaid eye made of colored glass. Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Barnet and Dandridge 2006}. |
|  | **1043** | Cast reproduction of an aquamanile after removal of its investment, still retaining the evidence of its sprueing. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Barnet and Dandridge 2006}. |
|  | **1044** | Radiograph showing the integration of square-sectioned iron armature elements extending up out of Aristotle’s arm and leg. The sharp bend at their tops suggests a point of overlap with additional elements and a potentially different technical approach to the fabrication of armatures. Aquamanile in the Form of Phyllis and Aristotle, southern Netherlands, late 14th or early 15th century, H. 32.5 cm (Metropolitan Museum of Art, Robert Lehman Collection, 1975, inv. 1975.1.1416). See {Barnet and Dandridge 2006}. |
|  | **997** | Side view. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). To see the location of the detail in **fig. 503**, click to activate the overlay. |
|  | **998** | Detail of top, showing seam lines. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1007** | X-radiograph from the side without the lid. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **1009** | Detail of the relief decoration across the surface and of the uneven corrosion or patina. Huo Ritual Vessel, 11th century BCE, Middle Yangtze Valley, China, H. 17.2 cm (Freer Gallery of Art, Smithsonian Institution, Washington, DC, purchase—Charles Lang Freer Endowment, inv. F1936.6a–b / Department of Conservation and Scientific Research). |
|  | **963** | Statuette of Avalokiteśvara (?), Bangladesh, 8th–early 9th century, H. 8.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 507). See {C2RMF Internal Report 2021}. |
|  | **434** | Front view. Ten-Armed Avalokiteśvara, Java, first half of the 9th century, H. 34 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3816). See {Mechling et al. 2018}. |
|  | **964** | Statuette of Vasudhārā, central Java, second half of the 9th century, H. 13 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 2255). See {Mechling et al. 2018}. |
|  | **161** | Kubera/Jambhala, Java, ca. late 9th–early 10th century, H. 17 cm (Musée National des arts asiatiques – Guimet, Paris, inv. MG 3619). See {Mechling et al. 2018}. |
|  | **423** | Front view. Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **437** | Front view. Vairocana, Java, first half of the 10th century, H. 15.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 18290). See {Mechling et al. 2018}. |
|  | **447** | X-radiograph of frontal view. Statuette of Jambhala, central Java, first half of the 9th century, H. 28 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3814). See {Mechling et al. 2018}. |
|  | **425** | Detail showing engraving and punch marks. Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **1055** | Profile of an engraving made in the metal on the front piece of the cloth of the Statuette of Jambhala, as measured by digital microscopy. The vertical axis reports the depth and the horizontal axis the width of the engraving (both in µm). The surface of the bronze is represented by the horizontal green dotted line. The cross section of the engraving and its dimensions are represented by the red curve. The maximum depth appears to be ~0.6 mm (600 µm), and the width at the surface is ~2 mm (2000 µm). See the altered V shape of the imprint (blue arrow), which demonstrates that the engraving in the metal was made by following a line already in the wax model. Statuette of Jambhala, central Java, first half of the 9th century, H. 28 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3814). See {Mechling et al. 2018}. |
|  | **445** | X-radiograph of frontal view. Vairocana, Java, first half of the 10th century, H. 15.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 18290) See {Mechling et al. 2018}. |
|  | **442** | Bottom view. Vairocana, Java, first half of the 10th century, H. 15.5 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 18290). See {Mechling et al. 2018}. |
|  | **444** | X-radiograph of side view. Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **1048** | Annotated neutron radiograph of side view, showing more clearly than the X-radiograph (**fig. 515**) the contours of the sealing material (red overlay) and some of the consecration offerings. For an even better visualization of the consecration offerings, see tomographic images of a related figure (**figs. 403, 404**). Kubera/Jambhala, Java, first half of the 10th century, H. 18 cm (Musée National des arts asiatiques – Guimet, France, inv. MG 3625). See {Mechling et al. 2018}. |
|  | **487** | Tin and lead content of the alloys of the Javanese statuettes from the Musée national des arts asiatiques-Guimet, Paris. One dot represents one statuette (wt%, ICP-AES analysis on drillings). See {Mechling et al. 2018}. |
|  | **488** | Main impurities in the metal of the Javanese statuettes from the Musée national des arts asiatiques-Guimet, Paris. One bar represents one statuette, sorted by chronological group (wt%, ICP-AES analysis on drillings). See {Mechling et al. 2018}. |
|  | **1051** | Tin content in the metal of Javanese statuettes from the Musée national des arts asiatiques-Guimet, Paris. One bar represents one statuette, sorted by chronological group (wt%, ICP-AES analysis on drillings). See {Mechling et al. 2018}. |
|  | **1053** | Example of Thai statuette cast in an unleaded tin bronze (11 wt% Sn, 0.6 wt% Pb, ICP-AES analyses) with a surface enriched in tin by depletion (~20 wt% Sn, PIXE analysis). Avalokiteśvara Maitreya, found in the Prasat Hin Khao Plai Bat II cache, northeast Thailand, late 7th–first half of the 9th century, H. 46 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 3321). See {Bourgarit et al. 2003}; {Mechling et al. 2018}. |
|  | **1052** | Example of Thai statuette cast in an unleaded high-tin bronze (16 wt% Sn, 0.4 wt% Pb, ICP-AES analyses). Buddha in Vitarkamudrā, Mon culture of Dvāravatī, central Thailand, 7th–8th century, H. 19 cm (Musée National des arts asiatiques – Guimet, France, inv. MA 3785). See {Bourgarit et al. 2003}; {Mechling et al. 2018}. |
|  | **1110** | Geopolitical map showing tin deposit locations in Southeast Asia as revealed by geological surveys carried out since the 1960s (this does not include deposits in adjacent southern China and India). Courtesy of Sébastien Clouet, ongoing PhD work (2019–22): “Les mines d’Angkor, provenance et circulation des métaux non ferreux dans le Cambodge angkorien (IXe-XVe siècle),” Faculté des Lettres – Sorbonne Université, Paris. |
|  | **574** | Jean Bullant (French, 1515–1578), Anne de Montmorency Funerary Heart Monument, 1571, H. 128 cm (Musée du Louvre, inv. MR1681-1683). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}; {Castelle et al. 2021}. |
|  | **542** | Overlay of interpretive technical diagram and both X-radiograph and daylight photography. Barthélemy Prieur (French, ca. 1536–1611), Peace, cast in 1571 by Nicolas Péron, H. 128 cm (Musée du Louvre, inv. MR1683). See [Case Study 5](#CaseStudy5). |
|  | **591** | Two different recipes for clay-based cores in Early Modern French large bronzes, as illustrated by the distribution of different sizes of quartz inclusions in the clay. The size is represented on the horizontal axis by the maximum dimension of the grains (Feret). The number of quartz grains for each size is represented on the vertical axis by the surface ratio (the total surface of all the grains having the same size divided by the total surface of all grains). Recipe 1 shows only one size (red arrow on the left graph). Recipe 2 includes two sizes of quartz inclusions (see the two red arrows on the right graph). See [Case Study 5](#CaseStudy5), {Castelle, Coquinot, and Bourgarit 2016}. |
|  | **606** | Barthélemy Prieur (French, ca. 1536–1611), Funerary Genius, Christophe de Thou Monument, 1583–85, L. 109 cm (Musée du Louvre, inv. MR 1685). See {Seelig-Teuwen, Bourgarit, and Bewer 2014}. |
|  | **127** | Simon Guillain (French 1581–1658), Louis XIV as a Child, ca. 1647, H. 153 cm (Musée du Louvre, inv. MR 3232). See {C2RMF Internal Report 2021}. |
|  | **594** | Histograms showing the alloy composition (ICP-AES analysis) of the three Virtues adorning the Anne de Montmorency Funerary Heart Monument, 1571, H. 128 cm (Musée du Louvre, inv. MR1681-1683). See [Case Study 5](#CaseStudy5), {Castelle et al. 2021}. |
|  | **357** | Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **364** | The first page of the \*American Machinist\* story describing the molding of bronze statuary at the Griffoul foundry. The article shows, step by step, the production of Charles Russell’s \*Medicine Whip\*. \*American Machinist\*, December 5, 1912, 923. |
|  | **970** | Charles Russell’s \*Medicine Whip\* featured in \*American Machinist\*, December 5, 1912, showing Griffoul foundry sand mold with chef-modèle on sand before embedding. |
|  | **968** | Detail side view of horse’s head and neck showing artist’s modeling. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **969** | Detail side view of Indian’s leg and horse’s belly showing artist’s modeling. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **976** | Detail of artist signature made in a soft material prior to casting with a partial fingerprint above and rows of possible punch marks made after casting. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **345** | Detail showing the Griffoul foundry mark cast through from the model. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **973** | Sand mold showing sand piece-mold pieces covering model prior to backfilling. Charles Russell’s \*Medicine Whip\* featured in \*American Machinist\*, December 5, 1912. |
|  | **974** | Sand mold disassembled and ready for baking. Channels on right side of image (yellow overlay) will direct molten metal into the mold and gases out. Charles Russell’s \*Medicine Whip\* featured in \*American Machinist\*, December 5, 1912. |
|  | **967** | Detail side view of head and shoulders. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **366** | The bronze cast of \*Medicine Whip\* at the Griffoul foundry after removal from the sand mold, before fettling and finishing. The sprues (yellow overlay) have yet to be removed, and the ends of the core vents are protruding (green overlays). Threaded screws were cast into the hooves for mounting (orange overlay). \*American Machinist\*, December 5, 1912, fig. 14. |
|  | **360** | Detail of back showing tool marks where a sprue was removed. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **359** | Detail of horse’s rear showing tool marks (circled in red) where core vent hole was repaired after casting. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, sand cast 1912–16, H. 14.8 cm (Gilcrease Museum, Tulsa, 0837.14). |
|  | **975** | Annotated sand mold showing core (A); core vents protruding from core (B & C); channel cut to direct molten metal (D); vent (E); and screws inlaid to attach base after casting (F). Charles Russell’s \*Medicine Whip\* featured in \*American Machinist\*, December 5, 1912. |
|  | **972** | Detail of head and shoulders of the Indian. Charles Marion Russell (American, 1864–1926), \*Medicine Whip\*, modeled 1911, lost-wax cast by the California Art Bronze Foundry 1927–28, H. 27.6 cm (Amon Carter Museum of American Art, Fort Worth, inv. 1961.96). |
|  | **705** | Reduced-scale 3D resin print of an artist-made model to be used as a %%foundry model%% for producing smaller bronze %%variants%%. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **930** | Annotated X-radiograph showing the flashing that formed along the juncture between different core materials—ceramic shell (in the muzzle) and plaster/clay mixture—as a white line of uneven density halfway up the horse’s head. An internal core support wire was inserted to connect the two core sections (red line). A line around the neck (green line) corresponds to TIG welding to join two separately cast parts. Remnants of sprues appear as denser patches (blue overlays). Note that the use of beam limiting shutters (used to reduce X-ray scatter, see [II.3](#II.3)) have caused underexposure of the lower quarter and the right edge of the radiograph. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **726** | The artist lifting the hot mold out of the casting pit after casting. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **715** | Core pin being pierced through the wax cast. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **745** | Bright arc of the TIG welder during the joining of two sections. Andrew Lacey (British, b. 1969), \*The Anatomy of Bronze\*, cast by the artist in 2019, Devon, UK, H. 45 cm (artist’s collection). |
|  | **1097** | Experimental reproduction cast of the head of the Apollo of Lillebonne during the 2016 CAST:ING meeting, Coubertin, France. Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **28** | One aspect of chasing can involve enhancing detailed surface decoration. Here a V-shaped graver is used to reinforce the lines of the lion’s mane cast through from the model, where they had been incised into the wax. Ubaldo Vitali (American, b. 1944), Reproduction of a Lion Aquamanile, Maplewood, New Jersey, 2006, H. 19 cm, after Aquamanile in the Form of a Lion, probably northern Germany, 12th century, H. 19.5 cm (Metropolitan Museum of Art, gift of Irwin Untermyer, 1964, inv. 64.101.1491). See {Dandridge 2006}. |
|  | **982** | Detail showing the artist’s signature and the edition number that were inscribed in the wax. Joan Miró (Spanish, 1893–1983), \*Personnage\*, designed 1976, cast 1985, H. 213.4 cm (J. Paul Getty Museum, inv. 2005.116). |
|  | **1113** | Examples of both hand and electric tools used in modern art foundries for fettling and possibly chasing include (from the left): hammer and chisels, tin snips, grip pincher, angle grinder fitted with a cutting blade, rotary disk sander, reciprocating saw. |
|  | **1098** | Plaster chef-modèle used to sand cast a two-thirds-scale bronze reproduction of the head of the Apollo of Lillebonne during the 2016 CAST:ING meeting, Coubertin, France. Original: Apollo of Lillebonne, France, 1st century BCE–1st century CE, H. 193 cm (Musée du Louvre, inv. Br37 [NIII65]). See **fig. 288**. |
|  | **476** | The backs of all four gilded brass reliefs show identical gouge marks—evidence that they were sand cast from the same carved wooden pattern. Relief figures of Benjamin Franklin, purportedly cast by Paul Revere (American, ca. 1735–1818) after a wood model by Simon Skillen, from Joseph Pope’s (American, 1750–1826) Grand Orrery, 1776–87, H. 31 cm (Collection of Historical Scientific Instruments, Harvard University, inv. 0005). |
|  | **177** | Gilded Standing Divinity, Cambodia, Angkor, Siem Reap province, 11th century, H. 130.8 cm (Metropolitan Museum of Art, from the Collection of Walter H. and Leonor Annenberg, inv. 1988.355). |
|  | **981** | Wax inter-model formed using a plaster piece mold. Note the core pins inserted into the wax. Andrew Lacey, 2018. |
|  | **980** | Investment mold used to cast a small bronze (mold height ~32 cm). Andrew Lacey, 1998. |
|  | **1105** | Diagram depicting a type of inversion casting: 1) core pins are inserted into a hollow wax model; 2) the sprue system is fused onto the wax model; 3) the wax model is invested in a refractory material; 4) the mold is then heated until dry and all traces of the wax melted and burned out; 5) meanwhile, a simple receptacle that will serve as a crucible is shaped of refractory material; small pieces of bronze and charcoal are placed in the crucible, which is luted to the mold to form an enclosed unit; 6) the mold-crucible is heated until the metal is molten; 7) the mold with its integral crucible is then inverted to allow the liquefied bronze to pour quickly into the mold; the charcoal helps to reduce oxidation; 8) fettling includes breaking off the refractory mold, removing the core pins, and cutting away the sprue system; 9) chasing may consist of polishing, burnishing, and the addition of details as needed; the surface color may also be enhanced with inlays, coating, plating, and/or patination. |
|  | **768** | Detail of dancer’s head showing how the bronze reproduces the blob of wax that Degas used in his original model to reinforce the jawline (green overlay). The cast also captures the quick gesture with which he pressed wax in to form the eye socket and pinched the displaced wax out into a fine ridge to form the nose, and the streak of his fingerprint up the side of the dancer’s head (indicated by the white arrows). Edgar Degas (French, 1834–1917), \*Grande Arabesque, Third Time,\* ca. 1885–90, H. 40.6 cm (Harvard Art Museums / Fogg Museum, bequest from the Collection of Maurice Wertheim, Class of 1906, 1951.78). |
|  | **118** | Bronze heated on a charcoal hearth being poured from a crucible into a plaster investment mold (Andrew Lacey studio, 2016). |
|  | **451** | The Youth of Agde, France, 1st century CE, H. 140 cm (Musée de l’Ephèbe et d’Archéologie Sous-Marine de la Ville d’Agde, France, inv. 839). See {Mille 2012}. |
|  | **1103** | Andrew Lacey (British, b. 1969), sprued wax model reconstruction after Andrea Riccio (Italian, ca. 1470–1532), Satyr and Satyress, 1510–20, H. 24 cm (Victoria and Albert Museum, presented by Art Fund, inv. A.8-1949). |