Wooden Artifacts Group

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MECKA BAUMEISTER, LISA ACKERMAN, JESSE NG, AND IVO KIPRE

Digital 3-D Reproduction and CNC Milling: Putting the Finial Touches on an Architectural Highlight, the Cassiobury House Staircase

ABSTRACT—For the reinstallation of the late-17th-century wooden staircase from the country house at Cassiobury Park (Hertfordshire) in the Met's new British galleries, it was necessary to create three replacement newel post finials. Laser scanning of the most well preserved original finial was carried out and losses were reconstructed in the digital 3D model. The final data was used to CNC mill reproductions from solid blocks of oak originating from a reclaimed balcony beam of an 1872 church. The new finials were hand finished by a professional carver and their surfaces treated to blend in with the staircase.

1. HISTORICAL CONTEXT

A highlight of British architectural works of art in the Met's collection is an elaborately carved wooden staircase (#32.152) from around 1680. The staircase was purchased from the London dealer Edwards & Sons of Regent Street in 1932, but it was not installed until 1956 (Parker 1957). Figure 1 shows how the staircase was presented in the British galleries, rising in three flights to a balustraded landing, from 1957 to 2017. When the European Sculpture and Decorative Arts curators responsible for the new British galleries decided to reinstall the staircase in a different location, it was essential to understand its original appearance and configuration, and its history to develop an appropriate concept for its conservation and presentation. Although this article focuses on the reproduction of the finials, our article based on the presentation given in the AIC Architecture and Objects Specialty Groups joint session on Historic Houses provides an overview of the entire staircase project. This article entitled *Reactive, Proactive, and Interactive: The Conservation and Reinstallation of the Cassiobury House Staircase at the Met*, by Mecka Baumeister, Lisa Ackerman, Nick Pedemonti, and Ivo Kipre, will be published in the 2020 OSG postprints, expected in 2021.

The staircase originates from the country house at Cassiobury Park in Hertfordshire (Rabbitts and Priestley 2014), which was enlarged for the First Earl of Essex, Arthur Capel, by architect Hugh May between I672 and 1680. Retaining one wing of the Elizabethan house, May added two wings. The Met's staircase was the principal one in May's building, and according to the ground floor plan published by John Britton in 1837, it rose in two long flights with a landing in between (Britton 1837, plate 2).

Around 1800, George Capel, the Fifth Earl of Essex, started rebuilding Cassiobury House in the neo-Gothic style after designs by James Wyatt, which was completed after Wyatt's death in 1813 by his nephew Jeffry Wyatville. The staircase was moved during this campaign to a different location in the house. The ground plan of the Gothic revival house shows that in the new installation the stairs rose in three flights—two long flights connected by one short flight—to a balustraded landing on the floor above (Britton 1837, plate 1). At that time the bottom five steps were opened up to provide a grander entrance to the staircase, the center newel post was added, and the bottom section of the balustrade was turned 90 degrees. The black and white photographs documenting this installation also indicate that the staircase had a dark surface finish (fig. 2).

When the Met acquired the staircase, it was thought to have been carved by Grinling Gibbons (1648–1721), the finest carver active in England in the late 17th century and early 18th century, whose works are known to have been left unfinished, with their wooden surfaces exposed. Presumably to reflect the aesthetic associated with Gibbons, the staircase was thoroughly stripped by the dealer before the museum bought it. In 1935, Christopher Hussey questioned the attribution of the Cassiobury staircase to Gibbons based on its similarities to the 1676 grand staircase at Sudbury Hall in Derbyshire by Edward Pearce (ca. 1635–1695). Hussey considered that Pearce possibly carved the Cassiobury staircase to whom it is now attributed (Hussey 1935).

Our research and examination revealed that the staircase originally had a decorative finish. Exposed tool marks support this notion, as carvers of such high caliber would not have left tool marks visible, unless they would be covered by ground and finish layers. Three different types of wood were used for the creation of the staircase: elm for the pierced and double-sided elaborately carved baluster friezes, the finials, and the pendants; oak for the steps and the landings; and pine for everything else (fig. 3). The use of different woods, including the inferior pine, is another indication that the staircase was originally intended to have a decorative finish that would have visually unified the disparate elements.

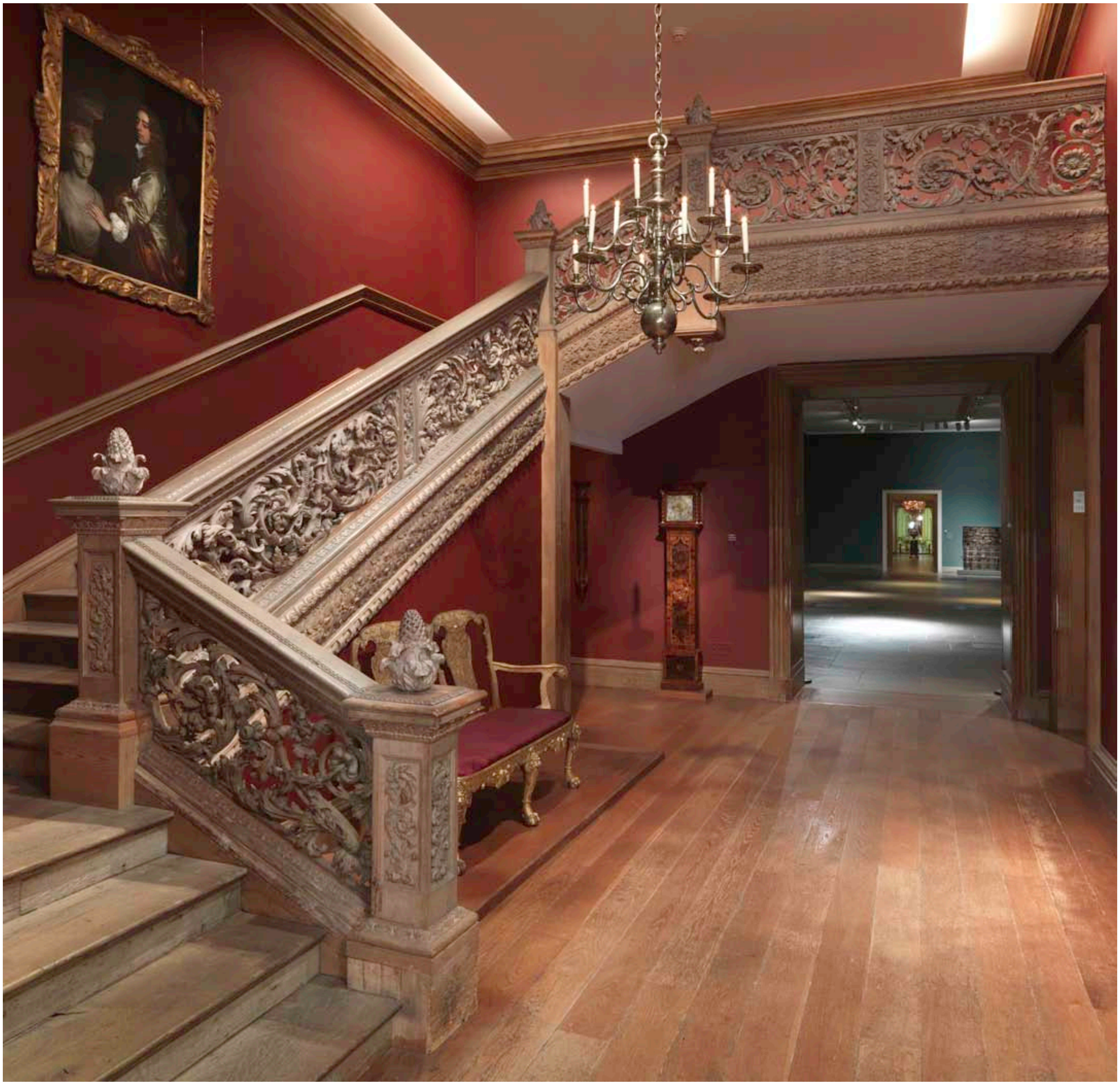


Fig. 1. Staircase from Cassiobury House in Hertfordshire as installed from 1956 until 2017 in the Met's British galleries (© The Metropolitan Museum of Art)

2. SURFACE EXAMINATION AND ANALYSIS

Considering that there is not enough evidence of the original or subsequent decorative surface treatments, it was decided that the wooden surfaces would remain exposed as part of the staircase's history. Our strategy, therefore, was to treat the elm, pine, and oak surfaces to produce a more harmonious appearance of the staircase. Most of the surfaces displayed a widespread whitish haze, a residue of the chemical stripping process. The haze was observed on both exposed and hidden areas, which suggested that the dismantled elements had been fully immersed in a stripping tank.

Instrumental analysis identified sodium sulfate (Na_2SO_4) in samples of this whitish surface residue, indicating that the staircase elements were likely stripped with a solution of sodium

Fig. 2. Staircase after it was reinstalled at Cassiobury House at the beginning of the 19th century. a. Lower long flight with the bottommost five steps opened up to provide a grander entrance; b. Balustrades of the short flight, the upper long flight, and the upper floor (©Victoria and Albert Museum, London. 'Cassiobury Park file, Furniture, Textiles and Fashion Department, V&A'. Unidentified print)

hydroxide (NaOH), followed by a neutralization treatment with sulfuric acid (H_2SO_4). This drastic method removed all decorative finishes, and altered the natural color of the surfaces, especially of the elm and oak. Other metal sulfates detected in the whitish deposits suggest that pigments and grounds containing lead (e.g., lead white), calcium (e.g., calcium carbonate), and other metal ions from the original and later surface finishes reacted with the stripping solution to produce the corresponding sulfur compounds. Please see the poster in Appendix 1 for more information about the scientific analysis of the stripped surface.

3. REINSTALLATION OF STAIRCASE

The overall concept for the reinstallation included presentation of the staircase, as much as possible, in its original configuration, with two long flights connected by one short flight with two quarter landings in between. A secondary aim was to allow visitors to use the stairs to fully appreciate the magnificent double-sided carving of the balustrades. Constrained by the ceiling height of the British galleries, we were only able to completely install the first long flight, one landing, and the short flight, leading to a mezzanine level with two small galleries which can also be reached by an elevator. From

Fig. 3. Balustrade of bottom short flight (BT). Three different types of wood were used for the creation of the staircase: elm for the pierced and double-sided carved baluster friezes, finials, and pendants; oak for the steps and landings; and pine for everything else. a. Exterior side; b. Interior side. (© The Metropolitan Museum of Art)

the second long flight and the landing on the floor above, only the balustrades were installed, supported by a steel structure. Given the insufficient ceiling height, the newel posts on the upper balustrade were installed without finials. In allowing the public to interact with this architectural masterpiece, a proactive approach was taken in determining the course of treatment.

4. THE FINIALS: THE FINAL TOUCH

The newel post finials represent pinecones resting on acanthus leaves. These seed-bearing fruits of pine trees were known as pineapples in Middle English and subsequently the same name came into use for the tropical fruit, creating ambiguity. "Pineapple" finials were envisioned for the staircase by Edward Pearce at Sudbury Hall, according to an accounting notation by its original owner, George Vernon: "Mr Peirce for carvinge – wthout ye Pinaples." Vernon apparently favored carved baskets with fruit and flowers over the proposed finials (Beard and Knott 2000). These were likely pinecones as well, since in the 17th century the exotic pineapple was a royal symbol and would not have been appropriate for the Cassiobury nor Sudbury staircase.

The elm finials are extremely fragile due to past insect infestation, chemical stripping, previous alterations, and repairs (fig. 4). Furthermore, it seemed likely that their prominent placement and tactile qualities would inadvertently encourage

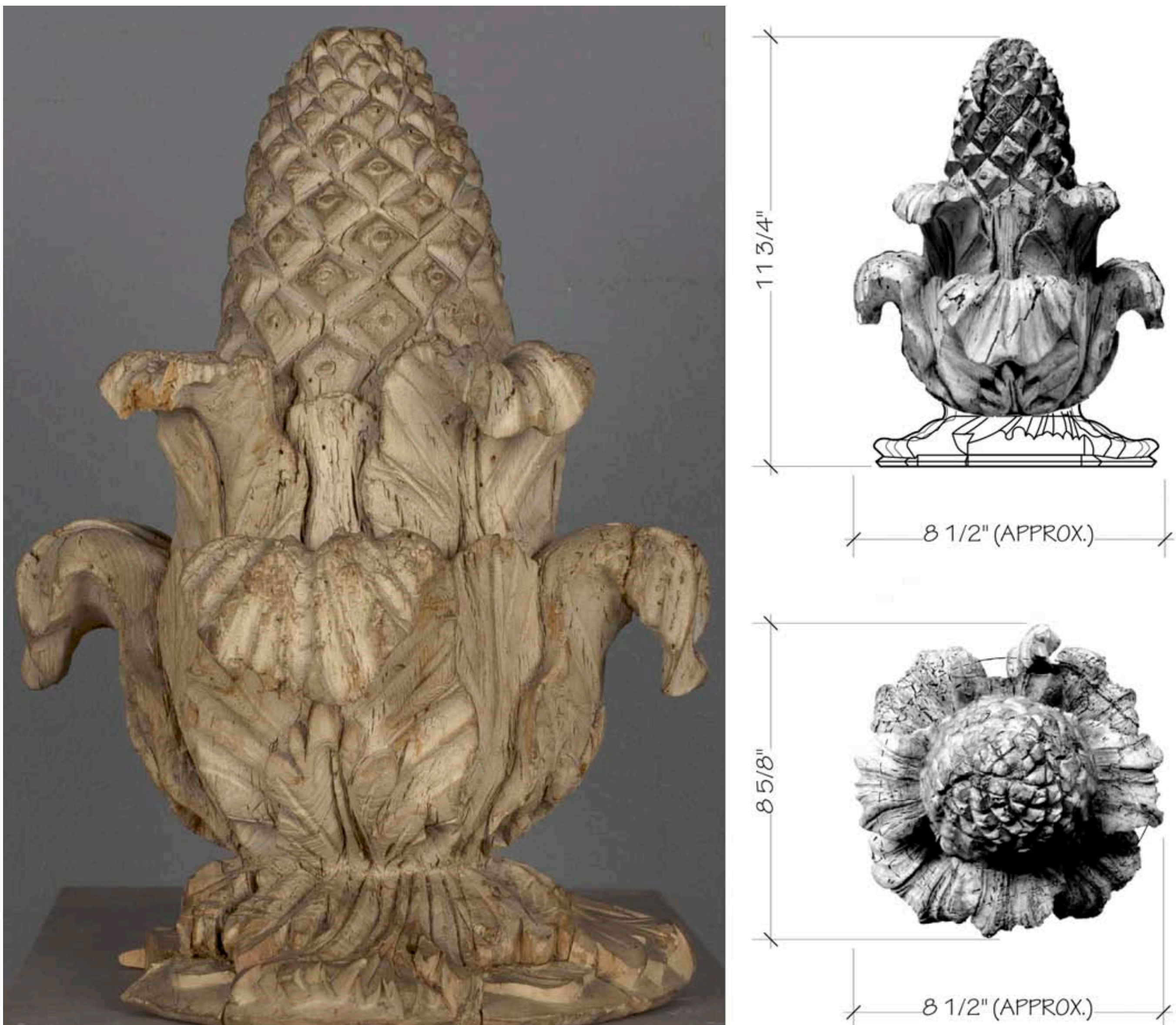


Fig. 4. Original elm finial (BT) and its dimensions (© The Metropolitan Museum of Art)

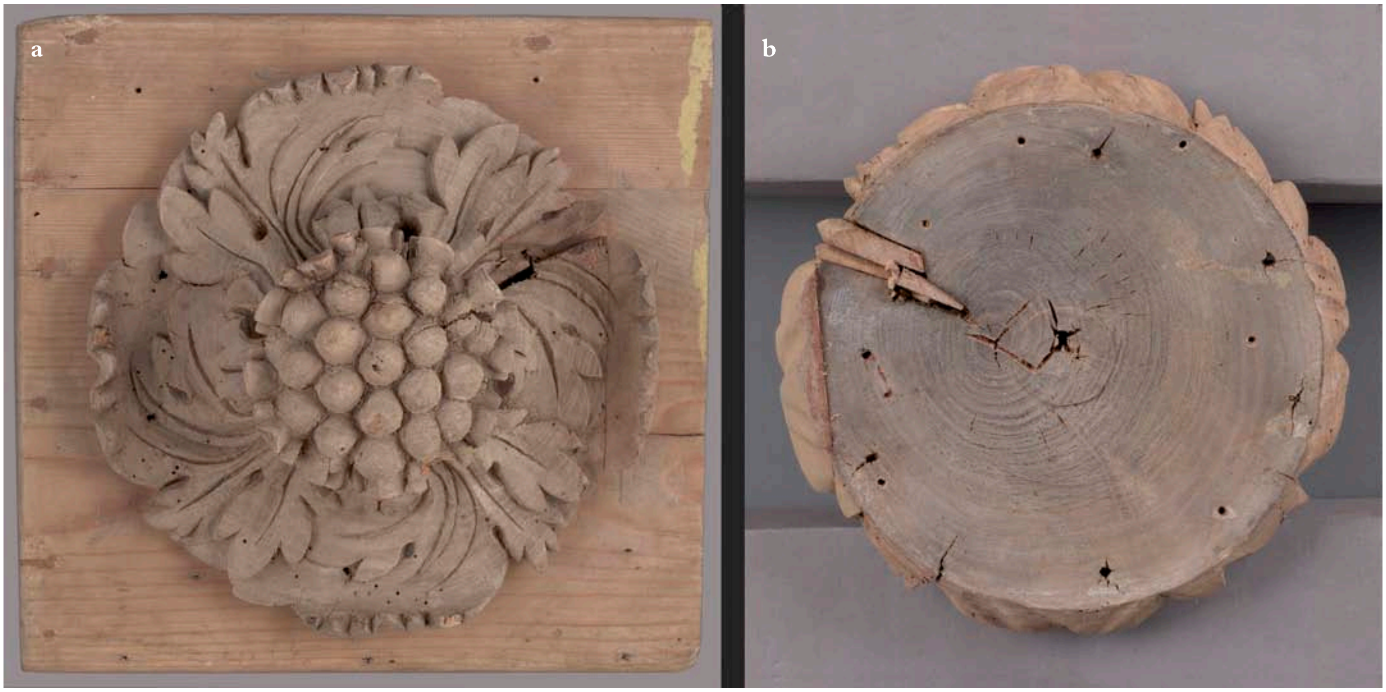


Fig. 5. a. Pendant attached to cap (BT); b. Unexposed side of removed pendant showing the pith and attachment point for the lathe used for turning the rough shape (DT) (© The Metropolitan Museum of Art)

the public to touch them. In view of these factors, we decided not to use the originals in the reinstallation, but to reproduce the three finials with a method that best evokes their original splendor. We also needed to replicate one elm pendant missing from the bottom of a suspended newel post. Like all reproductions for the staircase, the finials and the pendant were intended to conform to the original and blend in with the ensemble overall.

The original finials and pendants are each made from a solid piece of elm, including the pith, first turned on a lathe to attain their rough shape and then carved by hand (fig. 5).

After considering various options for reproducing the finials and the missing pendant, we concluded that laser scanning the most well preserved originals, digitally compensating losses, and using the final 3D model for CNC milling them in wood would produce the most faithful replicas. Prior to starting the reproduction process, all loose elements and most detached fragments were glued back in place and the surfaces were cleaned by brush vacuuming.

5. 3D IMAGING

The first step in the 3D reconstruction of the three finials was to capture as much data as possible from the original. There are a range of 3D scanning methods available, including structured light scanning, CT scanning, and photogrammetry, but laser scanning was chosen because of its metric accuracy and detailed geometry capture resulting in an accurate model that could be used to faithfully replicate original details in the milled reproductions. Considering that these would be made out of wood, there was no need to capture the texture, also known as the "color," of the original. The equipment used for capture was a Faro Laser Scanner arm tethered to *PolyWorks* software, which processed the scanning input and converted the object into a polymesh model. *PolyWorks* was also used to align multiple scans, as the finial had to be reoriented with respect to the scanner to reach deeper crevices and obscured recesses (fig. 6a).

6. POST-SCANNING PRODUCTION AND RECONSTRUCTION

After completion of the initial capture of the model, the next step was post-production processing. The raw model recorded losses and damages sustained by the original finial and had "holes," due to the absence of data in areas where the laser probe could not reach, especially the deeper crevices. All of these holes are indicated in green and yellow within the scanned model (fig. 6b). The 3D model was imported into a software called *Geomagic Wrap*, which allows these lacunae to be filled using a bridging method and a procedure known as automated hole filling. More problematic areas required complete reconstruction. Several of the larger missing or detached components, such as an extant fragment broken off from the base, a missing leaf, and a deep crack in the top part of the finial, as well as other smaller details, needed to be addressed. Utilizing the existing pattern design of the finial, the more complete components were duplicated and inserted into

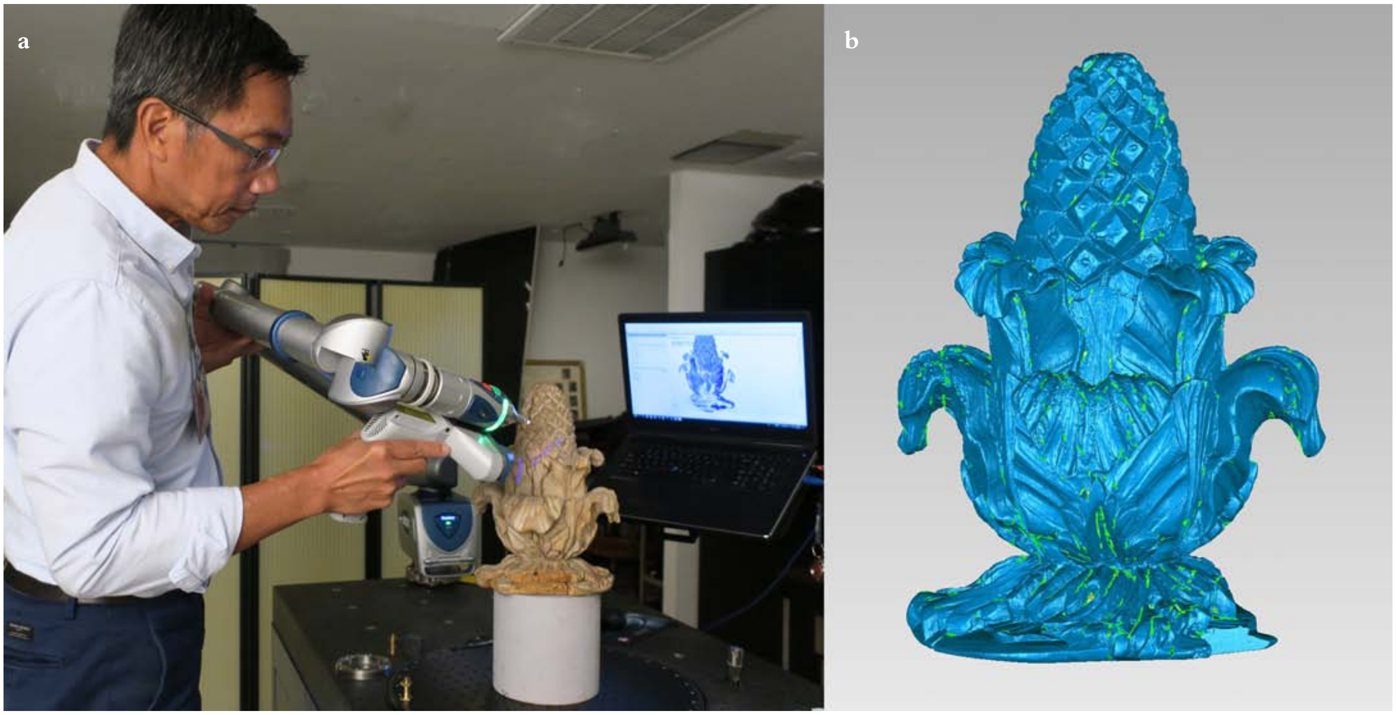


Fig. 6. a. Oi-Cheong Lee laser scanning the best-preserved finial; b. Resulting laser scan model (© The Metropolitan Museum of Art)

the losses. For the crack in the top, this required a slow shifting of the disrupted lozenge forms around the area to slowly close the gap. At the base, a detached fragment was scanned separately and then carefully fitted into the finial (fig. 7). After the main body of the finial was mostly complete, the greatest challenge was reconstructing the top of the pinecone, which was in poor condition and difficult to read in the original. To recreate this area, the damaged sections were first entirely erased from the model. The loss was reconstructed by carefully following the finial's spiral pattern, duplicating existing components and resizing them to mimic their decreasing scale as it got closer to the top (fig. 8).

Following the initial reconstruction of major areas, a modeling software called *Zbrush* was used to refine the model finishing the finer details especially where definition of details was needed in the leaves, and to sharpen edges. The software uses a range of brush tools to approximate a carved wooden surface. This modeling process was also essential for smoothing seams where new components were added.

6.1 MOUNTING CAVITY

The custom system for mounting the three finials on top of the newel posts, devised by conservation preparator Jody Hanson, required a cavity in the bottom of each finial. We decided that incorporating the cavity into the model would produce more precise and consistent results than cutting it directly into the milled reproductions. A cylinder of suitable dimensions was created in a CAD software called *Autodesk Fusion 360*. It was imported into *Geomagic Wrap*, placed at the center of the base on the model of the finial, and then inverted to form the requisite cavity.

6.2 3D PRINTED MODELS

Because losses and damages were compensated digitally, 3D printing of the model proved to be an essential step for reviewing its accuracy. A mixture of wood-infused PLA and white PLA, a polylactic acid vegetable-based plastic, was used as printing material. Several iterations were printed to check on the progress and fitting for the mount. These physical models were helpful aids for recognizing necessary refinements to the digital finial. Successive revisions were made to the 3D model until the final output was ready for milling (fig. 9).

6.3 COMPARATIVE ANALYSIS

When replacement elements of such magnitude are incorporated into a work of art, it is important to document reconstructive changes made to the original for future reference. By analyzing the original and final 3D models, the software *Geomagic Control X* generates custom reports diagramming the deviations from the original object. Discrepancies between the models are illustrated via color scales: green indicates no to minimal changes of the original surface, red indicates the addition of material (i.e., filling of losses and cracks), and blue indicates a reduction of raised areas (i.e., corrections of past restorations). Tolerance thresholds, measured in millimeters in this example of the pendant, can be adjusted to best represent alterations made to the original model (fig. 10).

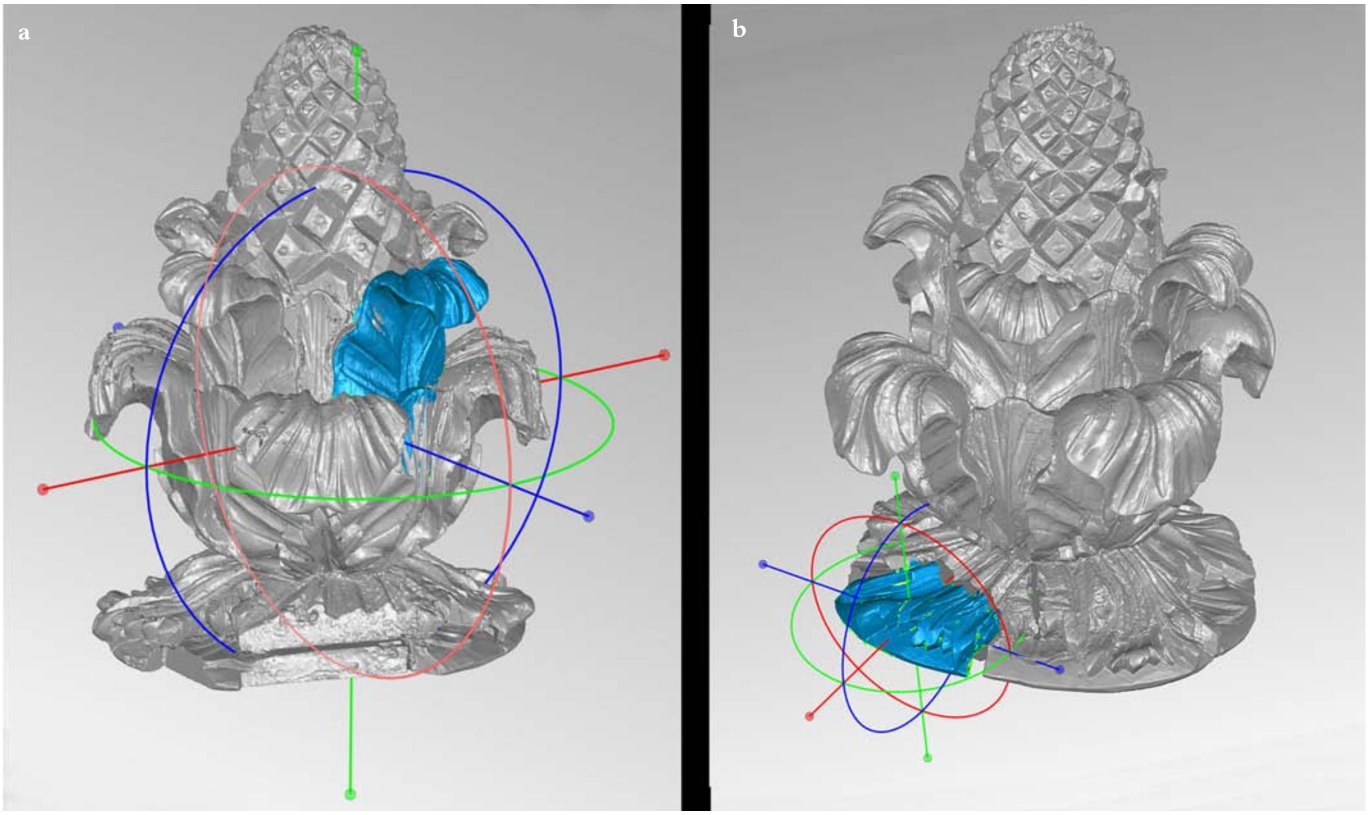


Fig. 7. Post-scanning production. a. Reconstruction of a missing leaf; b. Integration of a scanned element detached from the finial base (© The Metropolitan Museum of Art)

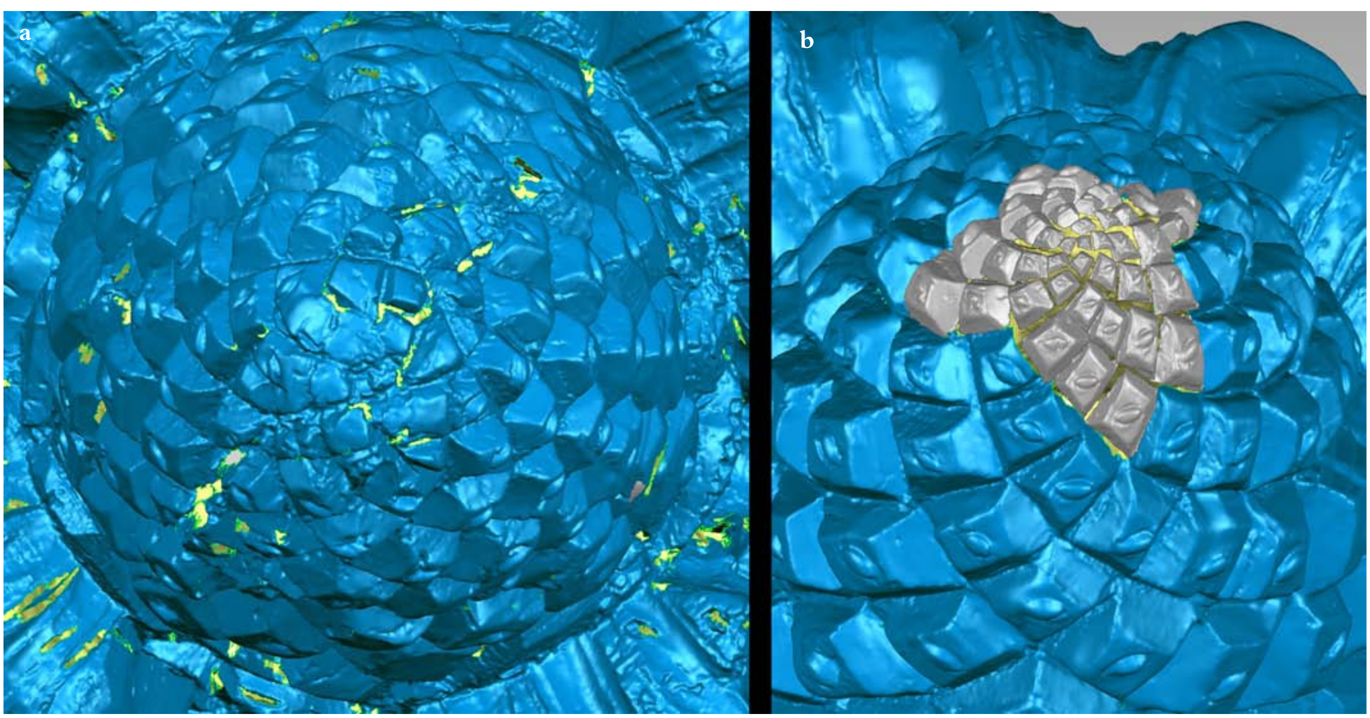


Fig. 8. Reconstruction of pattern on top of finial. a. Scanned damaged pattern with "holes" indicated in yellow and green; b. Reconstructed pattern (© The Metropolitan Museum of Art)

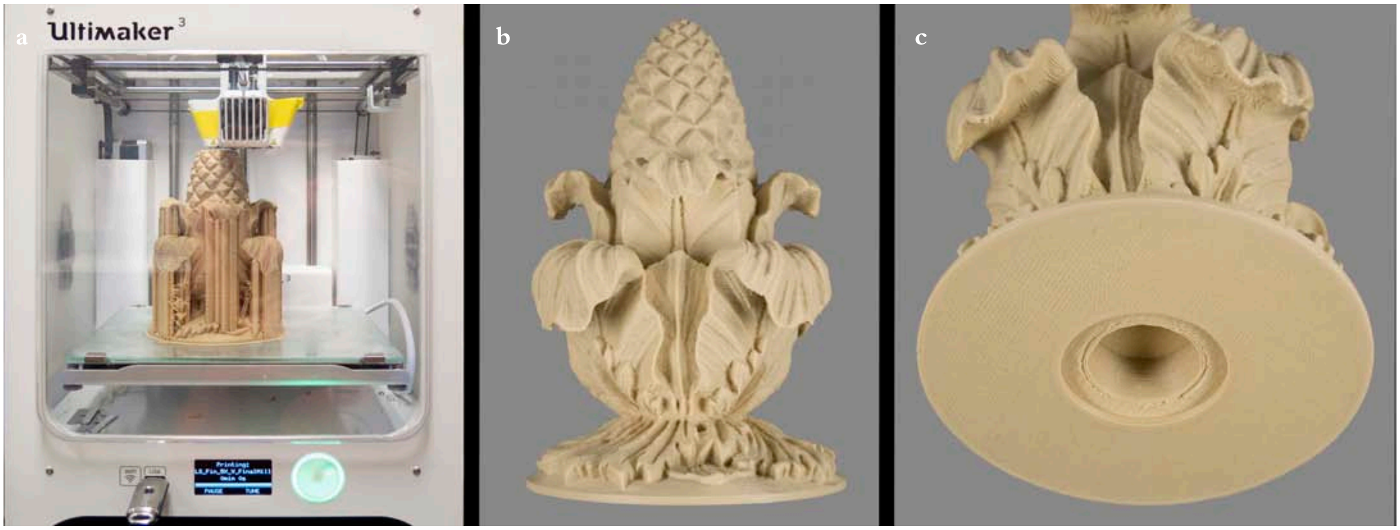
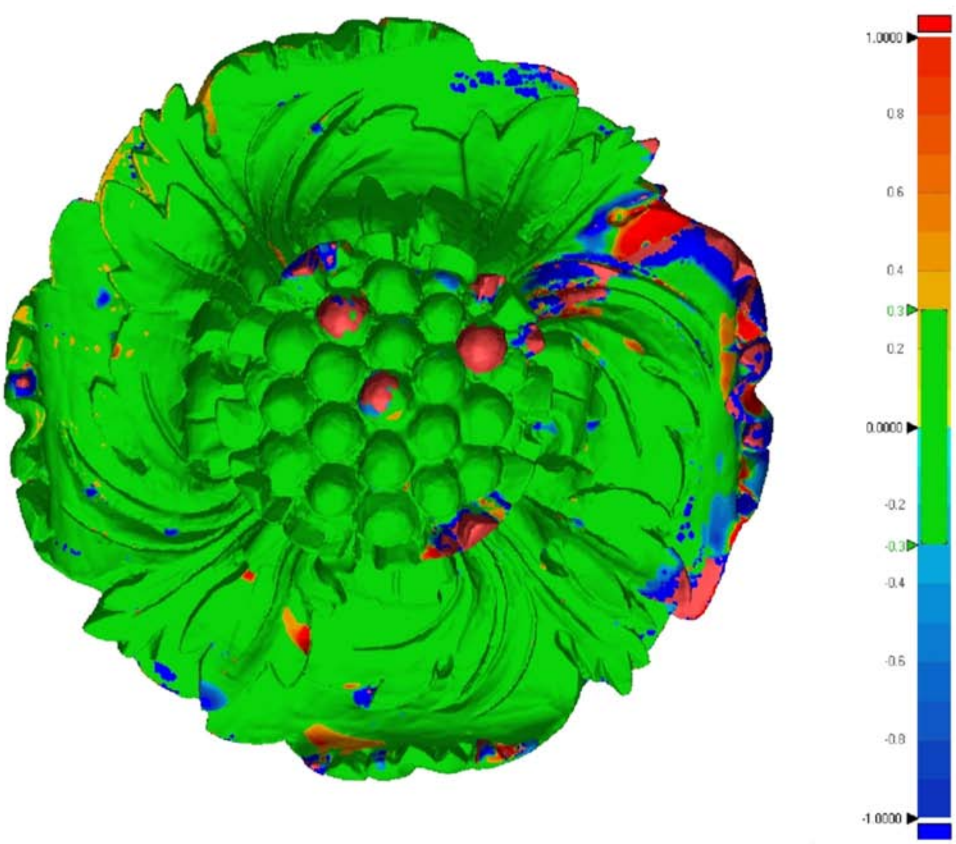
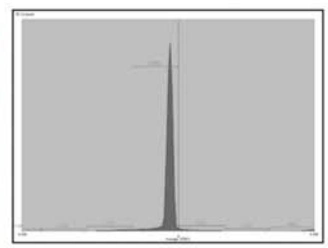


Fig. 9. a. Printing 3D model of finial; b. 3D print of finial; c. Underside of 3D print with mount cavity (© The Metropolitan Museum of Art)





Min.	-15.1218
Max.	15.1215
Avg.	0.5413
RMS	2.7357
Std. Dev.	2.6816
Var.	7.1909
+Avg.	1.2275
-Avg.	-0.4751
In Tol.(%)	82.6272
Out Tol.(%)	17.3728
Over Tol.(%)	7.1917
Under Tol.(%)	10.1811

Fig. 10. Comparative analysis between original pendant and reconstructed 3D model created with *Geomagic Control X* software. a. Green represents the original surface, whereas red and blue indicate deviations in reproduced areas measured in millimeters. b. Analysis and comparison data of deviations between the two models (© The Metropolitan Museum of Art)

7. CNC MILLING

For the physical output of the 3D models of the pendant and finals, we worked with Digital Atelier, a sculpture fabrication studio located in Mercerville, New Jersey. Digital Atelier specializes in CNC machine milling of highly complex and/or large objects, including works of art. The Met had previously worked with the Atelier in 2017 for Adrián Villar Roja's "The Theatre of Disappearance," a site-specific Roof Garden commission for which 16 objects from the museum's collection were laser scanned, milled from polyurethane foam, and painted (Roja, Adrián Villar 2017).

7.1 THE PENDANT

As a preliminary trial, we started with the pendant, which had been scanned and modeled following the same procedure discussed for the finial. Given that the natural brownish tone of the elm used for the finials and pendants was altered to a grayish tone by chemical stripping, for the reproductions we considered using ash, which is lighter in color but also a ring-porous wood. The challenge was to find a solid block of ash measuring 9 × 9 × 5 in. Unable to source solid well-seasoned ash in the requisite dimensions, we laminated five boards of approximately 2 in. thickness using an epoxy resin. After the adhesive was cured, the tightly sealed block was sent via overnight express to Digital Atelier for milling. Aware of the difference between the climate-controlled environment at the Met and the ambient environment at Digital Atelier, we were concerned about the impact this might have on the block. Our concerns were justified, because the laminated block separated during the milling along joints resulting in a detached fragment and the milling had to be stopped. We laminated another block of ash, improving every aspect of the process we could control, and were fortunate that only one joint opened after the pendant was milled. The joint closed within hours after its return to the controlled environment of the museum climate. Based on this experience, we knew that we could not use laminated ash for the reproduction of the much bigger and more elaborately carved finials with extensive undercutting. For these, it was essential to find three solid 9 × 9 × 15 in. blocks of a ring-porous wood.

7.2 THE FINIALS

After months of streamlined Internet searches, we found oak blocks offered by Jeff Schrier on Etsy as end tables. These had been cut from a beam salvaged from an 1872 Methodist church in Thorntown, Indiana (Thorntown Public Library n.d.). Sadly, the church community was not able to keep up with the repairs, and the brick building was demolished in 2017. According to the seller, the oak beam had been the main support of the floor joists in the second story sanctuary balcony. After an exchange of many videos, images, and measurements, we carefully selected the three best blocks. Like elm and ash, oak is a ring-porous wood, and it seemed a good choice.

Based on our experiences with the pendant and the condition of the oak beam from which the three blocks had been cut, a lot of preparatory work was required to ensure the best outcome for the finials. When the well-sealed block for the first finial arrived at the Met, the wood was acclimatized for several weeks before it was cut into a perfectly squared off octagonal-shaped block (fig. 11), which

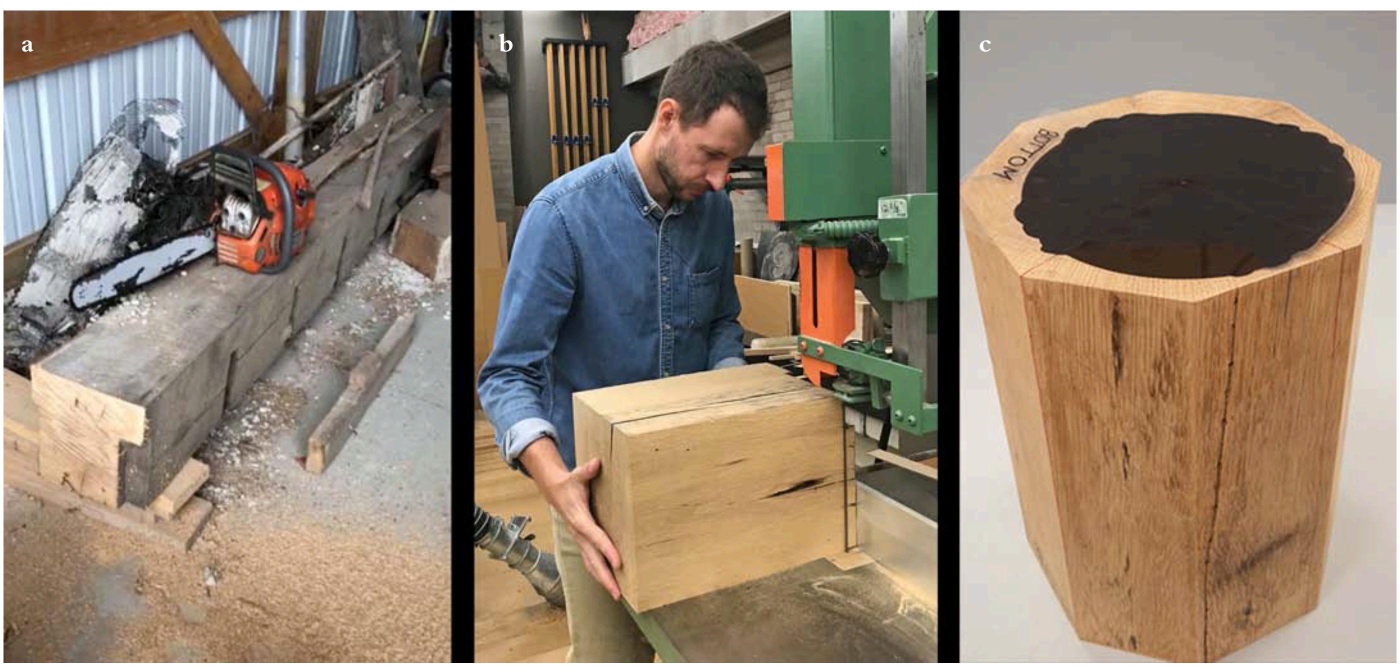


Fig. 11. a. Church balcony beam in Jeff Schrier's workshop; b. Ivo Kipre cutting the beam section into a perfectly squared-off block; c. The largest cross- and longitudinal sections from the 3D model were printed in a 1:1 scale on transparent Mylar to plot the finial in the octagonal-shaped block. (© The Metropolitan Museum of Art)

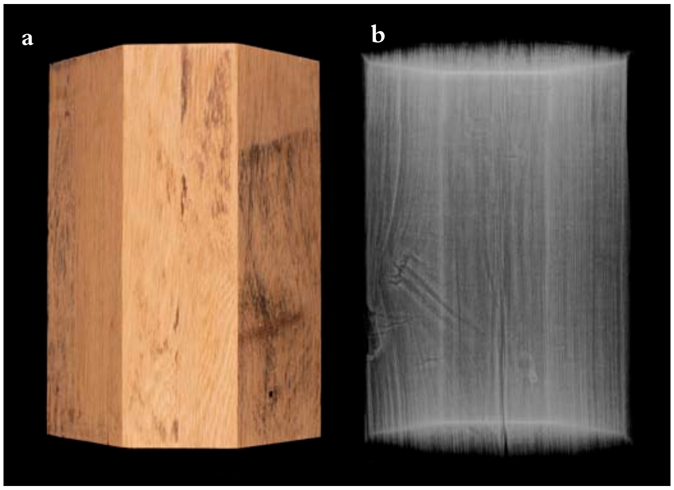


Fig. 12. a. Squared-off, octagonal-shaped oak block prepared for milling; b. Computed radiograph of oak block showing that no nails and screws remain in the block (© The Metropolitan Museum of Art)

Fig. 13. Oak block with milled cavity for mount. The center of the finial was placed away from the pith as much as possible. (© The Metropolitan Museum of Art)

was radiographed to ensure that it contained no nails or screws (fig. 12). To plot the finial within the block, the largest cross- and longitudinal sections from the 3D file were printed to scale on Mylar (fig. 11c).

Like the elm used for the original finials and pendants, the oak blocks contained their pith, from which several major cracks radiated. Concerned that these large cracks might cause sections of the wood to detach during milling, we proactively filled them with epoxy resin.

7.3 Milling of Finial at Digital Atelier

We brought the first block to Digital Atelier and were present for the milling. The wood was tightly packed and sealed to avoid fluctuations in temperature and relative humidity and thereby prevent additional cracking during transport. At their studio, we used the full-scale prints on Mylar, 1:1 photographs, and the 3D print to choose the best placement of the finial within the block. To minimize cracks that might radiate from the pith, we positioned the finial's center as far away from the pith as possible (fig. 13).

A five-axis CNC milling machine, with a machine envelope of 10 ft. along the X-axis and 5 ft. along the Y- and Z-axes and two rotational axes, was used to mill the finials. All router bits were made of solid carbide and bits descending from 3/4 in. to 1/16 in. were used. The 2020 *PowerMill* software programmed the CNC router. The file was decimated to 0.0005 in. tolerance in the *PolyWorks* software, whereas milling was done with 0.001 in. tolerance.

The cavity for the mount had to be milled first for which the oak block was secured to the table in the milling chamber (fig. 14a). As part of the clamping system for milling the finial, John Rannou at Digital Atelier milled a positive counterpart to the cavity out of a high-density foam that was attached to the oak block with screws. The process took about 56 hours to complete the milling of one finial (fig. 14, Appendix 2). This meant that after a long day, we left Digital Atelier empty handed and the finished finial was shipped to the Met two days later (fig. 15).

8. POST-MILLING PRODUCTION

During post-milling production, the epoxy fills were removed mechanically with saws and chisels and the open cracks were filled with oak. The oak wedges and other fills were cut from sections sawn off from the oak blocks, which allowed the growth rings and wood grain to be perfectly aligned (fig. 16). In order for the milled reproductions to reflect the surface texture of the original finials, Carole Hallé, a professional wood carver, was hired to hand finish them. Prior to Carole's arrival, we needed to do some more prep work. Volunteer Joseph Hutchins, assisted by Jody Hanson, drilled two holes concealed in the carving of each reproduction finial, which would be used to mount them during the carving process and also for the final installation. The holes were drilled with the head of the milling machine turned to the correct degree as specified in the drawing, and the finial was secured to an angled plate (fig. 17). A post was made to hold the finial in a swiveling vice giving easy access to all surfaces during the carving process. After the hand carving was completed, the oak surfaces were first sealed with isinglass, followed by a matt shellac, and a grayish wash of acrylic paint so that they would blend in with the rest of the staircase (figs. 18, 19).

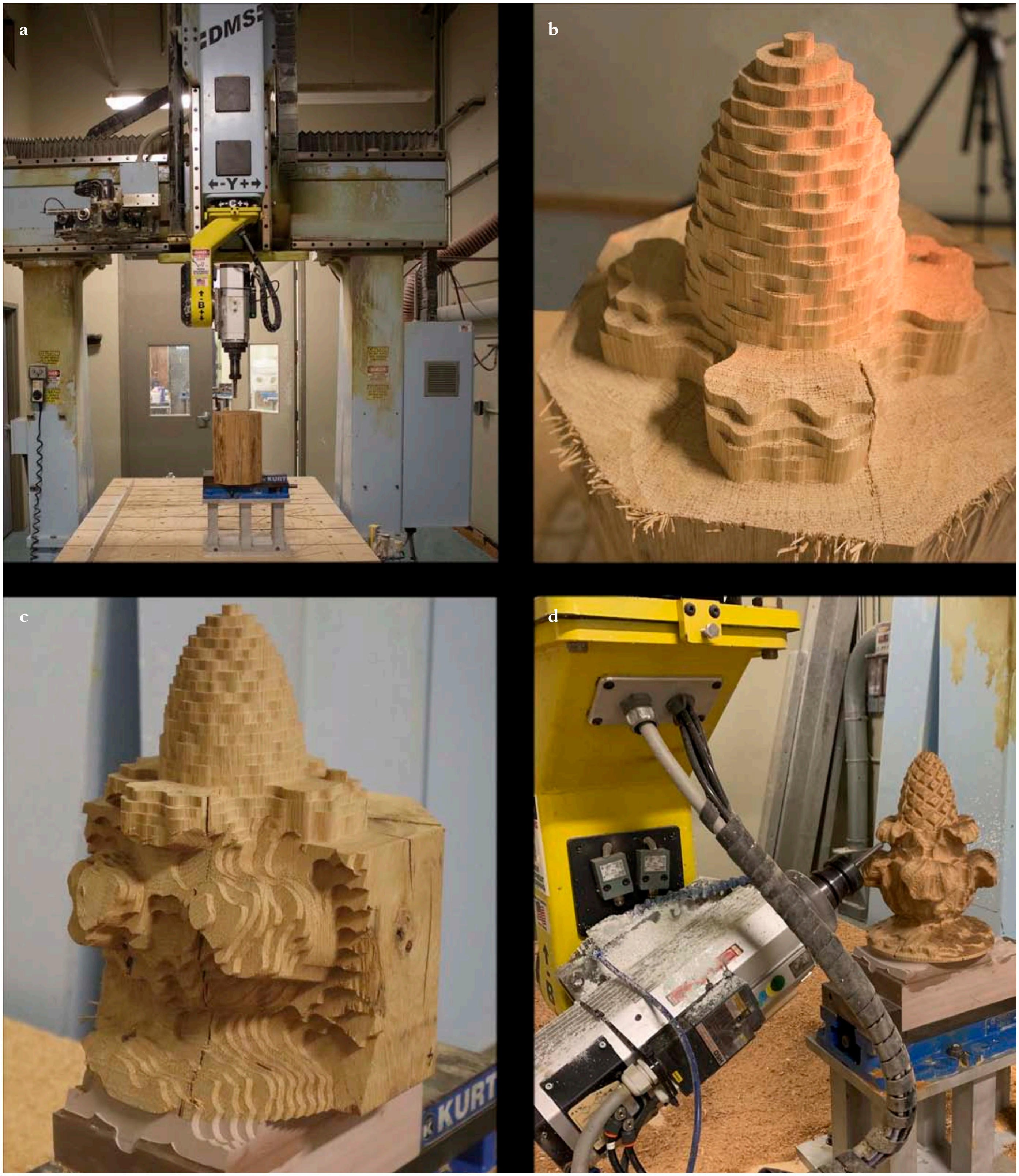


Fig. 14. Various stages of the CNC milling process. a. Milling cavity for the mount; b, c. The rough shape of the finial was milled with a 3/4 in. router bit. d. Finer bits were successively used to refine the final shape. (© The Metropolitan Museum of Art)

Fig. 15. Finial team at the end of a day's work at Digital Atelier. Back row: Nick Pedemonti, Jesse Ng, Mecka Baumeister; front row: Lisa Ackerman, Ivo Kipre (© The Metropolitan Museum of Art)

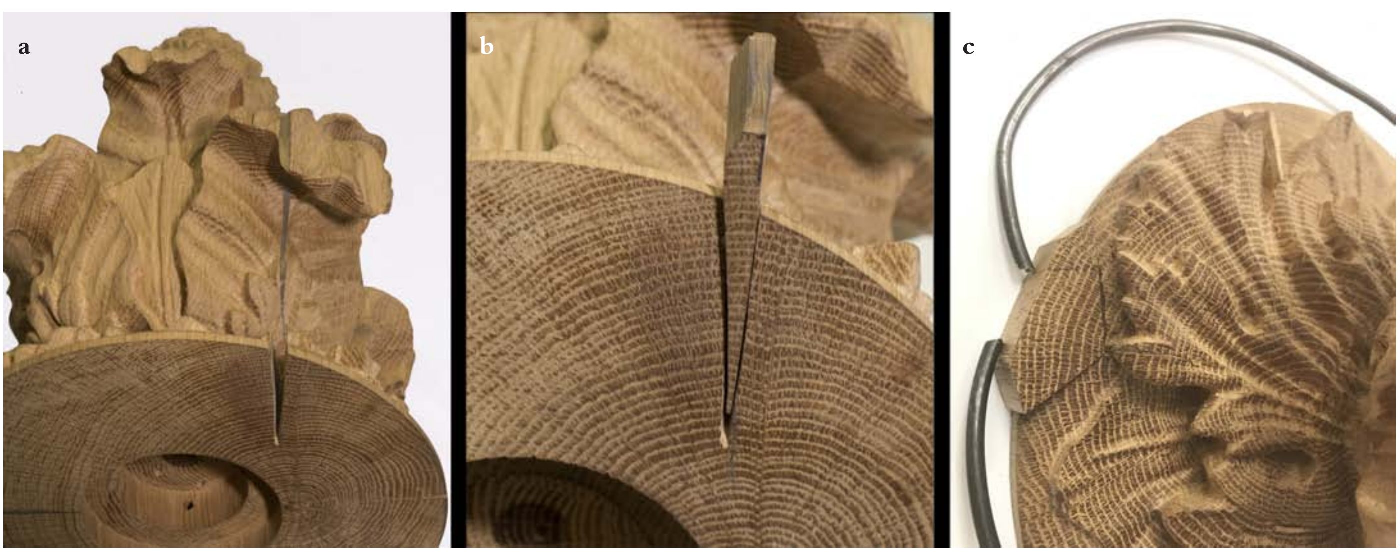


Fig. 16. Post milling production. Oak scraps trimmed from the block before milling were used to replace the epoxy resin fills and to fill open cracks. (© The Metropolitan Museum of Art)

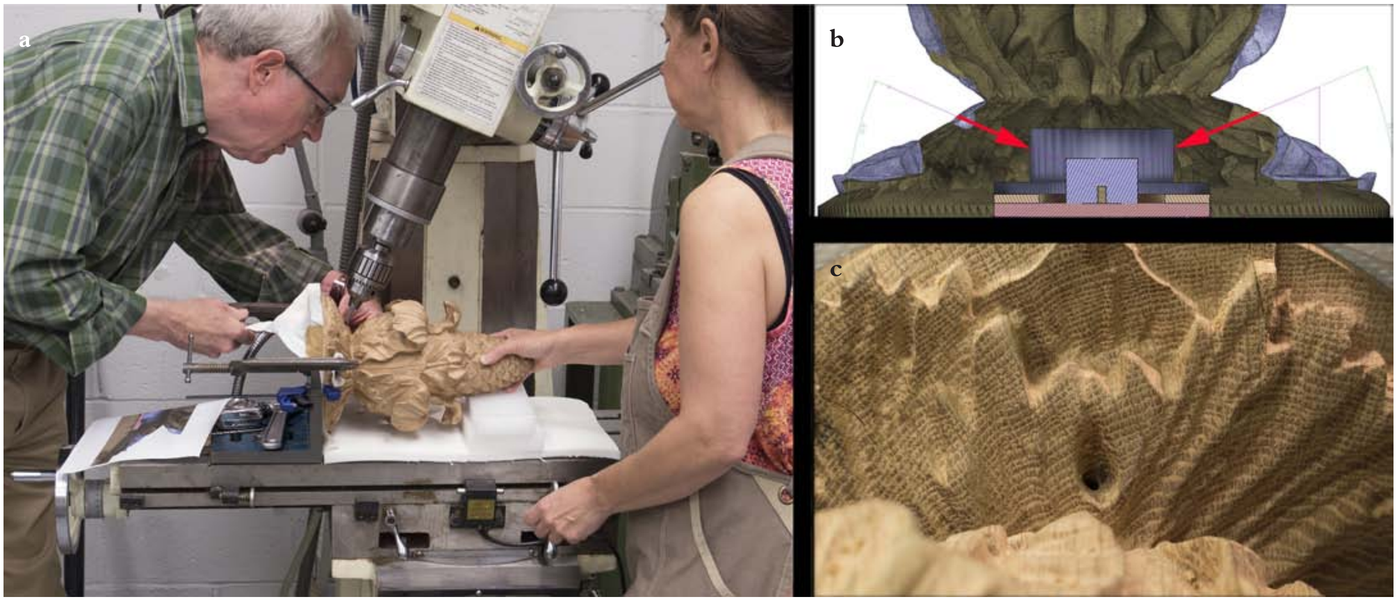


Fig. 17. Drilling holes into the finial base for attachment to mount. a, b. Joseph Hutchins and Jody Hanson drilling the two holes into the reproduction finials. The head of the milling machine was set to the correct angle as outlined in (b). c. The two holes for the screws were drilled in concealed places. (© The Metropolitan Museum of Art)

A custom system was made by Jody Hanson to mount the three finials on top of the newel posts. The attachment points and recesses from the last mounting of the original finials were reused. Brass strips were made to fill the recesses, and screws were used to join the mounts to the newel posts. The screws passed through the brass strips, extant holes in the top of the newel posts and connected to wood fills inside. An HDPE "plug" was secured in the brass collar of each mount with set

Fig. 18. a. Ivo Kipre clamping the oak fills; b. Carole Hallé hand carving the surface of the finial; c. Lisa Ackerman applying the surface finish (© The Metropolitan Museum of Art)

Fig. 19. Original finial (left); milled replica finial with hand-carved and sealed surface (center); completed replica finial (right) (© The Metropolitan Museum of Art)

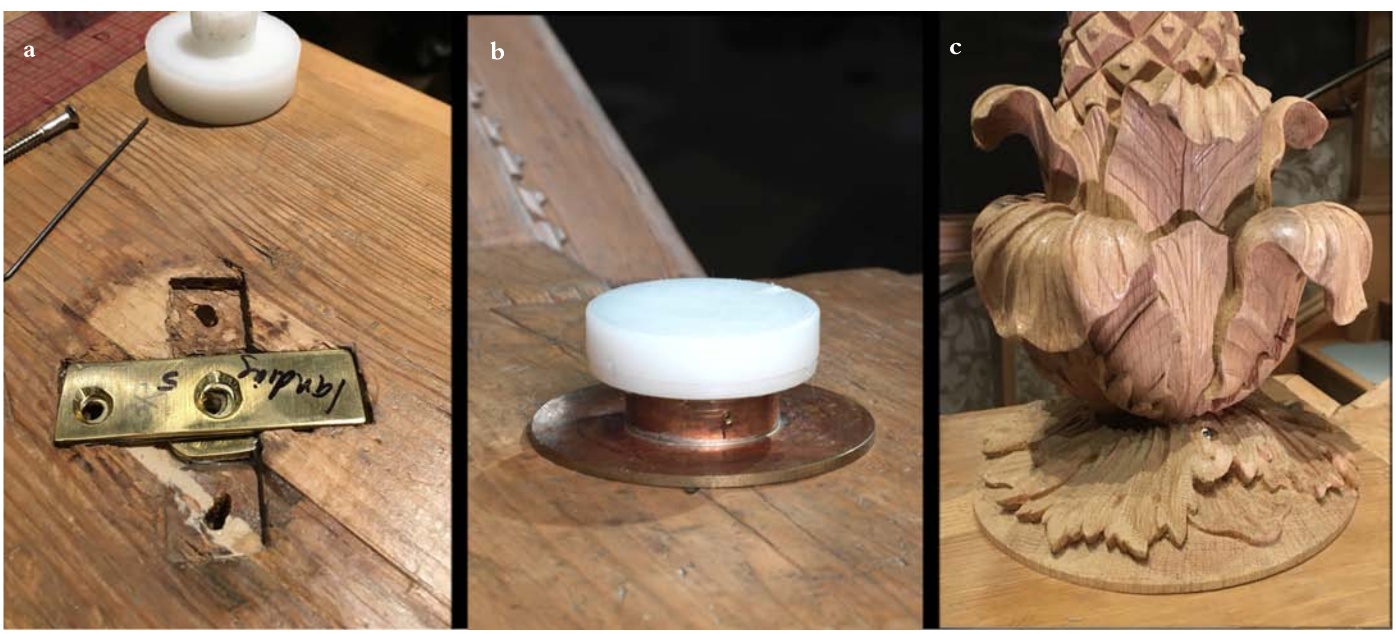


Fig. 20. Mounting the finial. a. Attachment points and recesses from mounting the original finials to the newel posts were reused by filling the cavities with brass strips that were screwed to the newel post; b. An HDPE "plug" was secured in a brass collar with set screws; c. The replica finial was attached with screws to the hidden mount. (© The Metropolitan Museum of Art)

Fig. 21. Reinstalled staircase with three replica finials in the new British galleries at the Met in 2020 (© The Metropolitan Museum of Art)

screws. HDPE was selected for its strength and because it is easily machined and tapped. When the finials were joined to the mounts, a brass bushing was used to guide the drill bit to extend the two screw holes in each finial base into the HDPE "plug" (fig. 20).

9. CONCLUSION

Mounting the finials was the final touch in bringing this architectural highlight of the British Galleries back to life. The image showing the reinstalled staircase illustrates how successfully the reconstructed newel post finials blend in with the original elements (fig. 21).

The reproduction of the finials by means of 3D laser scanning, followed by digital compensation of losses and damages, CNC milling of carefully sourced wood, hand carving, and surface finishing, was a collaborative project requiring the contributions of many specialists and produced, in our eyes, the most faithful replicas.

Given that each finial is made out of a solid block of well-seasoned wood, we anticipate that they will age in tandem with the other staircase elements. The finials and other carved details can be viewed close-up and enjoyed by visitors who choose to walk up or down the staircase as they progress through the new galleries.

APPENDIX

Power of pH 14 – interpreting and treating a stripped surface of a late 17th C. British wooden staircase

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THE MET

Introduction/ History

Among the architectural highlights in The Metropolitan Museum of Art is a carved wooden staircase from Cassiobury House in Hertfordshire (England) that dates to around 1680 **(Fig. 1)**. When first acquired in 1932, the staircase was thought to be the work of Grinling Gibbons (1648–1721) - the finest carver active in England at the time - whose works are known to have retained exposed wooden surfaces. To have the staircase look as Gibbons would have intended, the extant surface finish was thoroughly stripped before it was shipped from London to New York. The staircase has been reattributed to Edward Pearce (ca. 1635–1695), and on the basis of our examination and by comparison with similar contemporaneous wooden staircases, it is likely that it originally was painted. Unfortunately, surviving traces of earlier finishes do not provide enough evidence to determine how the staircase originally or subsequently looked.

Fig. 1 Staircase (32.152) from around 1680 made of elm, pine and oak (treads and risers) as installed in British galleries at The Met. Roger Fund, 1932.

Assessment of the stripped surfaces

Most elements of the staircase display a widespread whitish haze, possibly a result of an alkaline treatment aimed at stripping the surfaces to the bare wood. Its presence on both exposed areas and those hidden from view suggests that the dismantled elm and pine elements were fully immersed in a stripping tank **(Fig. 2)**. So far, scant and inconsistent white and reddish residues on the wooden elements have been interpreted as remains of original and/or later surface layers, and consist of lead white, calcium carbonate and red lead.

Fig. 2 Whitish haze on exposed and unexposed surfaces on a section of a pine handrail

White tide-line

Fig. 3 Whitish crystalline deposit at water-evaporation front on an unexposed section of a pine newel-post

Methodology

- ***X-ray fluorescence (XRF):*** analysis and depth of penetration of chemical elements *in-situ*
- ***X-ray diffraction (XRD), Raman micro-spectroscopy, Fourier-transform infrared micro-spectroscopy (µ-FTIR):*** molecular analysis of surface scrapings
- ***SEM/EDS:*** mapping of chemical elements in cross section of stripped wood
- **Surface *pH measurements (pH strips):*** evidence of alkaline/ neutralization treatment

pH measurements:
pH readings in the neutral range (6.3 to 8.0) on stripped pine surfaces, compared to those in the acid range (4.5 to 5.0), measured on surfaces subsequently trimmed (**Fig. 4**) are further evidence that the wood was treated with an alkaline solution and then neutralized with an acidic one. pH in the range of 4.5-5.5 would be typically expected for untreated pine wood.

pH 8.0 neutral range (stripped surface)
pH 4.5 acid range (1956-trimmed surface)

Fig. 4 Section of pine newel post trimmed for the 1956 installation at The Met

Molecular analysis:
The presence of sodium sulfate in the whitish residue on the surfaces (**Fig. 4**) including the white tide-line (**Fig. 3**) suggests that the elements of the staircase were stripped with a solution of sodium hydroxide (NaOH), followed by a neutralization treatment with sulfuric acid (H_2SO_4).

$$2NaOH + H_2SO_4 \longrightarrow Na_2SO_4 + 2H_2O$$

Gypsum and other metal sulfates detected in samples from the whitish surfaces suggest that pigments/ grounds containing lead (e.g. lead white), calcium (e.g. calcium carbonate) and other metal ions in/on the wood reacted with the solutions used for the stripping treatment to produce the corresponding sulfates.

Elemental analysis:
XRF mapping *in-situ* (**Fig. 5**) points to an accumulation of Pb, S and Ca on the surface of the pine wood. As opposed to Ca, which is present throughout the wood, Pb and S penetrated into the wood of a discreet gradient. While it was not possible to detect Na by XRF in the experimental conditions, SEM/EDS mapping in cross section indicated Na_2SO_4 crystals on the surface and penetration of Pb and S into the pine (**Fig. 6**).

Na_2SO_4 crystals
Visible light
SEM
Pb
Na
S

Pb Lα
S Kα
Ca Kα
1 mm spot size
1 cm

Fig. 5 XRF mapping (in-situ) on detail of pine element highlighted in a red square in **Fig. 4**. Elemental mapping for lead (Pb), sulfur (S) and calcium (Ca) shows their distribution on the surface and into the wood

Fig. 6 SEM/EDS mapping in cross section of pine wood from one of the handrails, showing elemental distribution of lead (Pb), sodium (Na) and sulfur (S) on the surface and in the wood

Fig. 7 Section of carved elm baluster frieze with whitish haze

Treatment challenge and concluding remarks

With the intention of presenting the staircase in a different location in the renovated British Galleries in 2019, a concept for its conservation treatment includes the removal or reduction of the whitish haze to improve its appearance. Preliminary experiments reducing the whitish appearance with agarose gels on a pine element seemed promising for controlled removal of the sodium sulfate salts. Reducing the whitish haze and discoloration on the carved elm baluster friezes (**Fig. 7**) and finials presents a greater challenge because elm is less resistant to acids and bases than pine. Further analysis will focus on how the stripping process affected both woods, in order to determine to what degree the damage may be mitigated.

Appendix 1. Poster Presented at the International Architectural Paint Research Conference *Powers of Ten: Expanding the APR Toolbox* at Columbia University in New York, March 15–17, 2017

Order	Approx. Time	Type of Strategy	Router Size	Offset from Surface
Roughing	6 hrs.	Offset roughing 0.5" step and 0.25" deep	3/4" endmill	0.1"
Semi finish 1	8 hrs.	Rotary mill 1 degree	1/2" ball	0.05"
Semi finish 2	10 hrs.	Many angles to get all the extra material removed leaving 0.05" extra material on overall surface 0.05" step over	1/2 " ball	0.05"
Finish 1	16 hrs.	Many angles to get all the areas on the whole surface that will fit a 1/2 ball 0.005" step over	1/2" ball	0.005"
Finish 2	8 hrs.	Many angles to get all the areas on the whole surface that the 1/2" ball missed, and the 1/8" ball will fit 0.002" step over	1/8" ball	0.002"
Finish 3	8 hrs.	Many angles to get all the areas on the top part that the 1/8" ball missed, and the 1/16 ball will fit 0.001" step over	1/16" ball	0.001"

Appendix 2. Timetable for Milling One Finial

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At the Met

European Sculpture and Decorative Arts: Sarah Lawrence, Luke Syson, Wolf Burchard, Ellenor Alcorn, Elizabeth St. George, Denny Stone; **Objects Conservation:** Lisa Pilosi, Keelia Jacobs, David Sastre, Nick Pedemonti, Frederick Sager, Jody Hanson, Joseph Hutchins, Deborah Schorsch; **Scientific Research:** Adriana Rizzo, Federico Carò, Yuka Ohashi; **Imaging:** Barbara Bridgers, Scott Geffert, Wilson Santiago, Richard Lee, Chris Heins, Oi-Cheong Lee, the late Ron Street; **Carpenter Shop:** Danny Olson, Vadim Danilov

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Carole Hallé; Jeff Schrier; John Rannou and Jon Lash at Digital Atelier LLC; Traditional Line Ltd.

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Word History. A Pineapple is an Apple (Kind of). How did this Tropical Fruit get tied to the Apple? https://www.merriam-webster.com/words-at-play/word-history-pineapple

SOURCES OF MATERIALS, EQUIPMENT AND SOFTWARE

Ash
Hearne Hardwoods Inc.
200 Whiteside Drive
Oxford, PA 19363
610- 932-7400
http://www.hearnehardwoods.com

AutoDesk. 2021. Fusion 360 Software. https://www.autodesk.com/products/fusion-360/overview.

FARO. 2021. FARO Laser Scanner. https://www.faro.com/.

G/flex 650 Toughened Epoxy (a versatile, liquid, 2-part epoxy; with a modulus of elasticity of 150,000 PSI, it is more flexible than standard epoxies making structural bonds that can absorb the stress of expansion and contraction)
West Systems
100 Patterson Ave.
PO Box 665
Bay City, MI 48707-0665
866-937-8797
https://www.westsystem.com/specialty-epoxies/gflex-650-toughened-epoxy/

Golden Fluid Acrylics
Golden Artist Colors Inc.
188 Bell Road
New Berlin, NY 13411
607-847-6154
https://www.goldenpaints.com/

High Tack Fish Glue (a cold-setting, water-soluble collagen adhesive)
Lee Valley Tools Ltd.
PO Box 20700
Reno, NV 89515
800-267-8735
http://www.leevalley.com/US/wood/page.aspx?cat=1,110,42965&p=20019

InnovMetric. 2020. PolyWorks Software. https://www.innovmetric.com/en.

Isinglass (an adhesive made from the swim bladders of sturgeon fish)
TALAS
330 Morgan Ave.
Brooklyn, NY 11211
http://www.talasonline.com/Sturgeon-Glue

Oak
Jeff Schrier
10300 w 800 n
Thorntown IN 46071
317-989-3144
https://www.etsy.com/shop/ReclaimedArtisans

Pixologic. 20201. ZBrush Software. https://pixologic.com/.

3D Systems. 2021. Geomagic Wrap and Geomagic Control X Software. https://www.3dsystems.com/software.

Shellac #12-1302 (an ultra-light dewaxed and decolorized shellac)
WoodFinishing Enterprises
1729 N. 68th St.
Wauwatosa, WI 53213
414-774-1724
https://woodfinishingenterprises.com/shop/shellac/dewaxed-ultra-light-shellac-german/

Shellac Flat (a matting agent containing silicon dioxide made specifically to decrease the sheen of shellac)
Homestead Finishing Products
1935 W 96th St.
Cleveland, OH 44102
866-631-5429
https://homesteadfinishingproducts.com

3D Printer Wood Filament (wood filament for 3D printing is an FDM [Fused Deposition Modeling] filament developed to print wooden-like objects; this filament is recycled wood combined with PLA filament and some binding polymers)
Gizmo Dorks LLC
9414 Gidley St.
Temple City, CA 91780
626-552-8582
https://gizmodorks.com/wood-3d-printer-filament/

Ultimaker^3 3D printer.
https://ultimaker.com/3d-printers/ultimaker-3

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MECKA BAUMEISTER, conservator, has worked in the Department of Objects Conservation at the Metropolitan Museum of Art since 1988. Her primary responsibility is the examination and treatment of furniture, wooden objects, and historic interiors in the Department of European Sculpture and Decorative Arts. She oversaw the conservation and reinstallation of the historic interiors in the Met's new British galleries, including the Cassiobury House Staircase and the conservation of furniture and wooden objects on display in the galleries. Address: The Metropolitan Museum of Art, Department of

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LISA ACKERMAN is an associate conservator at the Art Institute of Chicago, where she is restoring a Grinling Gibbons over mantle from the Cassiobury House. She was employed by the Metropolitan Museum of Art as an assistant conservator for the British Galleries Project, where she was part of the team responsible for the conservation of the Cassiobury House Staircase. She also focused on the mantelpiece wall from the Star Hotel in Norfolk, England, ca. 1600, as well as furniture and other wooden decorative arts from Britain. Lisa previously worked for other museums and private conservation firms. Address: 190 Messer Avenue, Depew, NY 14043. E-mail: lisa.ackerman2@gmail.com.

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IVO KIPRE joined the Metropolitan Museum of Art as an associate conservator for the British Galleries Project, where he was part of the team responsible for the conservation of the Cassiobury House Staircase. He also focused on the treatment of the historic oak floors in the museum's British Period Rooms and British furniture. Previously, Ivo worked at private furniture conservation companies—notably, Arlington Conservation Ltd. in London and Period Furniture Conservation in New York City. Address: 10 Old South Road, Aquinnah, MA 02535. E-mail: ivokipre1@gmail.com