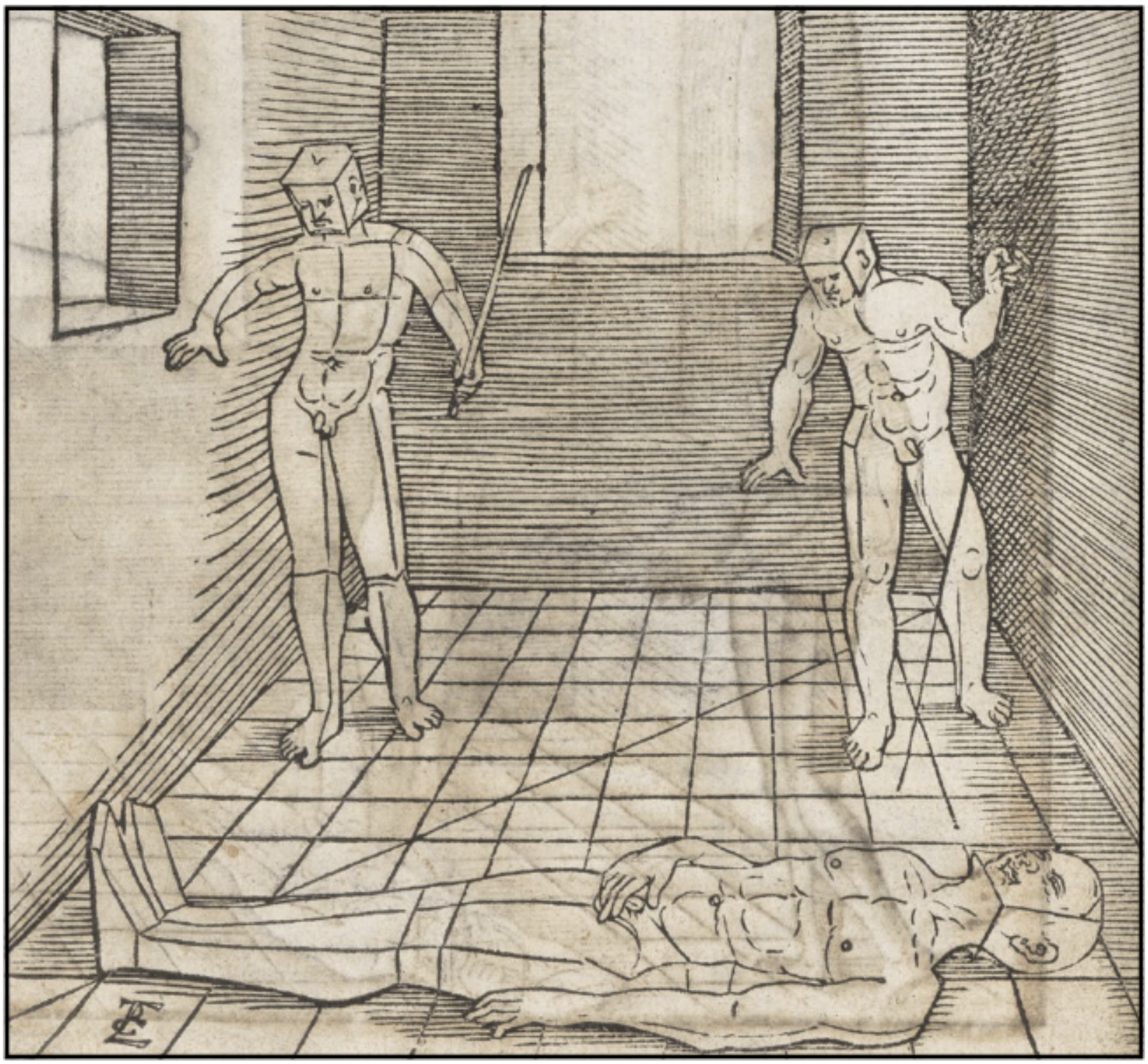
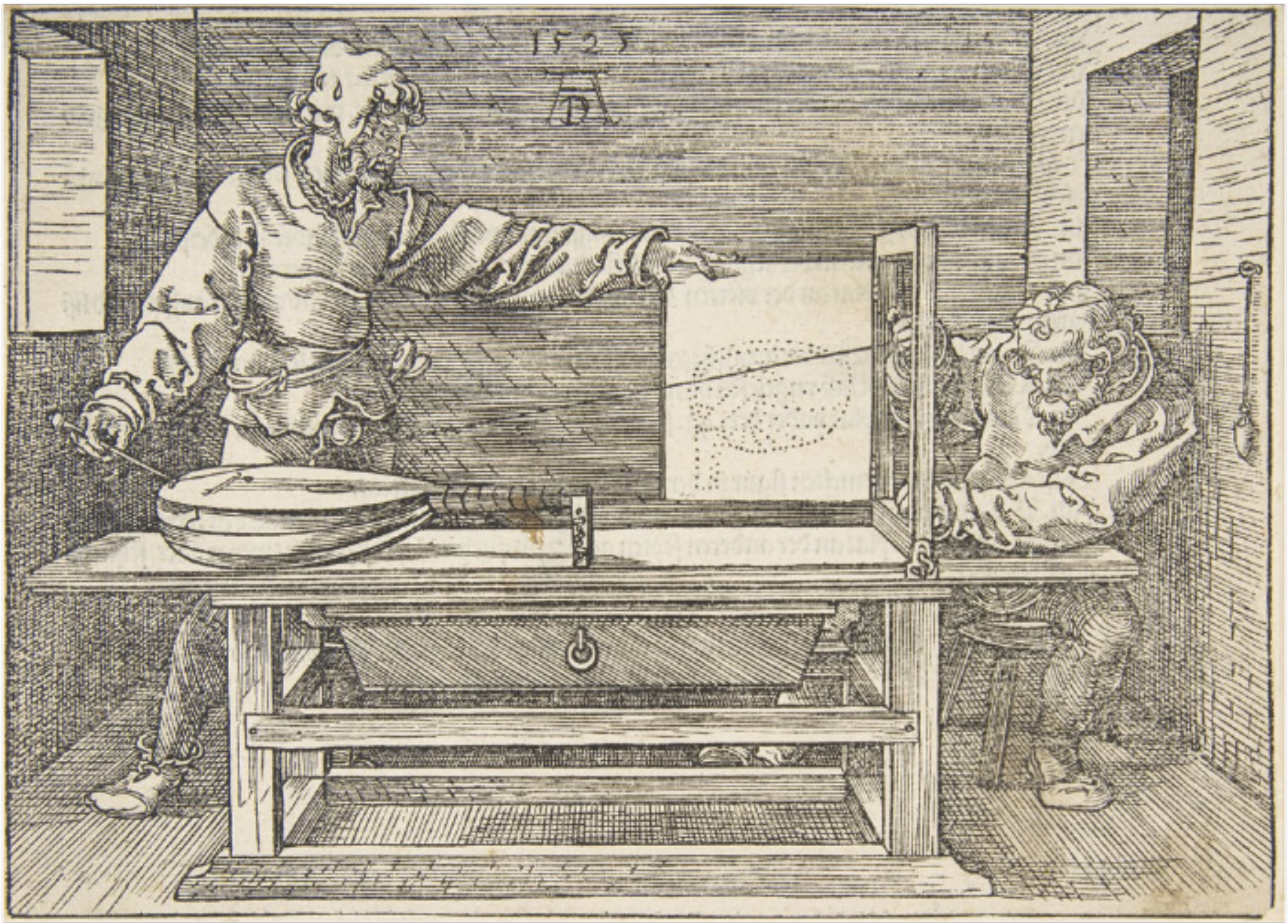
SPACE ODYSSEY

MARIO CARPO ON THE RISE OF 3-D TECHNOLOGY



Erhard Schön, *Underweissung der Proportzion und Stellung der Possen* (Instruction of Proportion and Position of Poses), 1538, woodcut on paper, sheet size 5⅜ × 7".



Albrecht Dürer, ***The Draughtsman of the Lute*****, n.d.,** woodcut on paper, sheet size $5\frac{1}{8} \times 7\frac{1}{4}$".

TODAY, IT IS almost a cliché to describe the rise of 3-D printing as a groundbreaking development. The notion that the technique represents a decisive turning point in the history of technology has gained widespread acceptance, with oh-so-grand pronouncements of its power coming from the likes of Barack Obama, Elon Musk, and even Martha Stewart. And as the technology has become increasingly accessible and widely adopted in the intervening years, the vision of a 3-D-printed world seems less like science fiction than like a rapidly approaching reality. Indeed, "*Mutations-Créations / Imprimer le monde*" (Mutations-Creations / Print the World), a major exhibition opening at the Centre Pompidou in Paris this month, offers just such a proposition, showcasing 3-D-printed products that are purportedly transforming a wide range of fields. Meanwhile, efforts are under way to adapt the technology to seemingly endless manufacturing applications, for the creation of everything from clothing to body parts. At the architectural scale,

house prototypes are already being 3-D-printed from concrete, and in 2012 Foster + Partners unveiled a design for a moon colony to be built by space-traveling robots equipped with 3-D-printing arms.

Yet all this emphasis on making, on the physical results of the 3-D-printing process, threatens to obscure a far more fundamental revolution. Three-dimensional printing is only the tip of the iceberg, just one of a host of digital techniques for scanning, visualization, and modeling that profoundly alter how we make things—but also how we understand and represent the world around us, how we see and what we experience. Until now, modern culture and technology have been largely image-based; images, in other words, were the primary means of recording and transmitting information about the world. But 3-D printing is merely the most visible symptom of a paradigm shift in global technology and culture from the visual to the *spatial*. And to fully grasp the magnitude of this change, we must look not only forward but back: to the entire development of technologies of reproduction and representation since the Renaissance. Here, *Artforum* invited architectural historian Mario Carpo to reflect on both the historical roots and the future implications of this looming technological revolution.

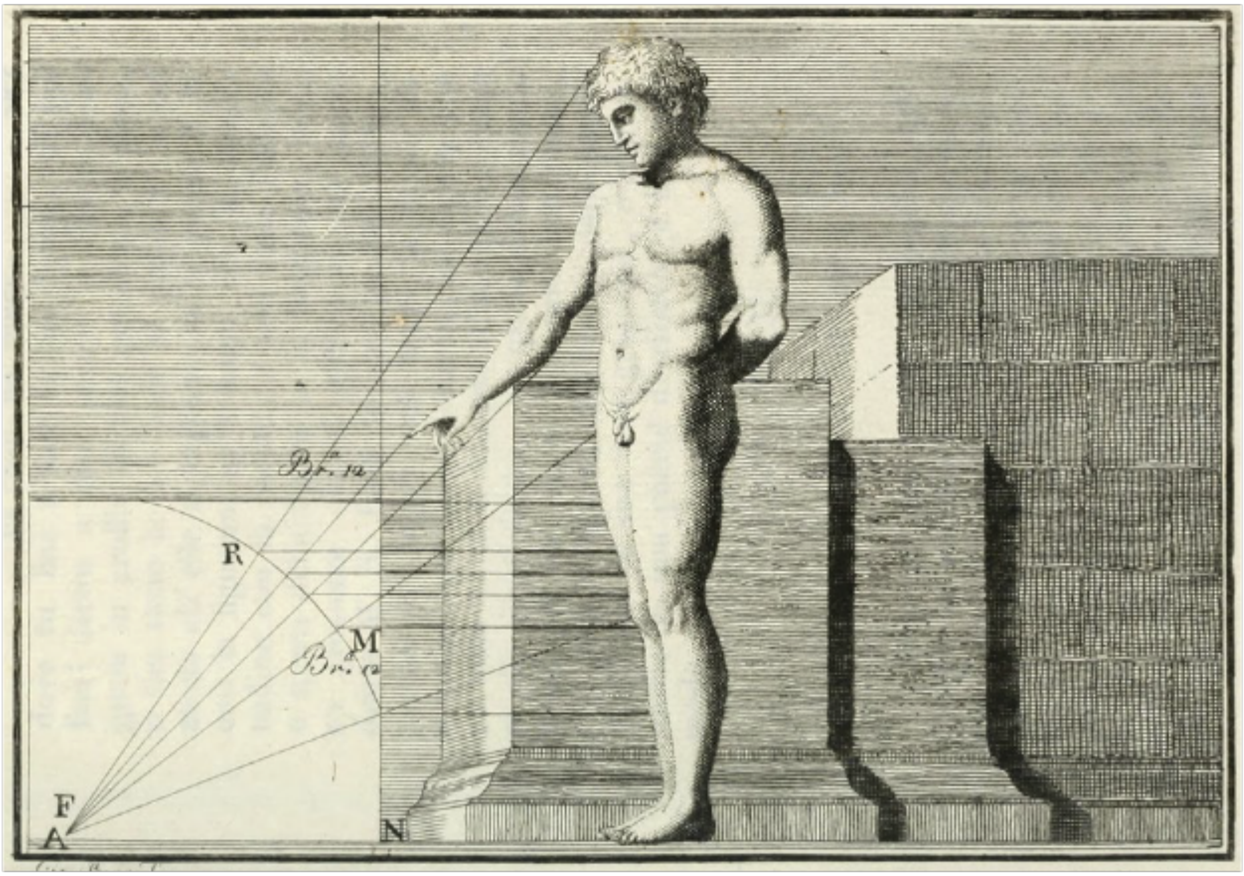
THE PROGRESS of contemporary digital technologies over the course of the past thirty years—from verbal to visual to spatial media—curiously reenacts, in a telescoped time line, the entire development of Western cultural technologies from the beginning of recorded history.[1] One generation ago, digital tools dealt almost exclusively with alphanumeric data; then came the rise of digital images, and today digital tools can easily manipulate all kinds of volumes in three dimensions. This is because words use less data than images, and flat, planar images use less data than volumes in space; as computers became more powerful and cheaper, digital notations could move from the alphabet to pixels to voxels.[2]

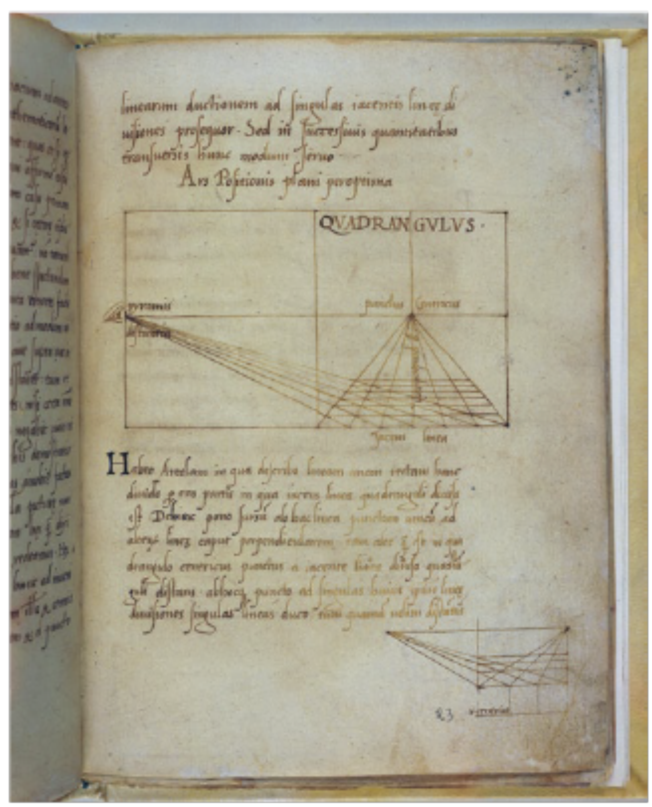
The same sequence already occured over a much longer period: Throughout classical antiquity and the Middle Ages, the main vehicle for the recording and transmission of data was verbal, not visual. Words were recorded and transmitted in space and time using the technology of the alphabet, but images were not. Classical and medieval authors had good reasons not to trust images: First, classical antiquity bequeathed, and likely knew, no geometric rules for making drawings—rules whereby every artist looking at the same thing

The cultural and technical primacy of modern, perspectival, projected images—and of images in general—is now drawing to a close.

would make the same drawing, and everyone looking at the same drawing would see the same thing. Second, no technology existed to make identical copies, so that each iteration of any given drawing was at the mercy of the will of individual copyists.

These two conditions changed suddenly and drastically in the Renaissance, due to the near-simultaneous emergence of perspective and of xylographic printing. Leon Battista Alberti's perspective (first described in his treatise *Della pittura* [On Painting], 1435) standardized the way images are captured: Once the geometry of a snapshot of the world is set by choosing the vantage point and the direction of the central visual ray, the resulting image is always the same—never mind if it is made by me, by you, or by a mechanical camera. This is because that image is a geometric projection, and Alberti's rules explain how to make that projection, and how to notate it once and for all. Print, in turn, standardized the way images are reproduced. Once a drawing is engraved on a mechanical matrix and printed, every copy of it will look the same. From their capture to their dissemination, modern images thus acquired a double guarantee of trustworthiness: true to nature when drawn by the artist; true to the artist's drawing when reproduced by the printer. These were, at long last, images that everyone could use and trust, and so everyone did: After many centuries of undisputed dominion of the word in the Renaissance, Western culture went visual,[3] and the dominion of the





Clockwise, from top: **Page detail from an 1804 edition of Leonardo da Vinci's *Trattato della pittura* (Treatise on Painting), 1651. Page from Leon Battista Alberti's fifteenth-century manuscript for *De pictura*,** ink on paper, 9 × 6½". **Lorenzo Lotto, *Triplice rittratto di orefice* (Goldsmith in Three Views), ca. 1525–35,** oil on canvas, 20½ × 31⅛".

Left: **Sir Anthony van Dyck, *Charles I in Three Positions*, ca. 1635–36,** oil on canvas, 33¼ × 39⅛". Above: **Philippe de Champaigne, *Triple Portrait of Cardinal de Richelieu*, ca. 1642,** oil on canvas, 23⅛ × 28¾".

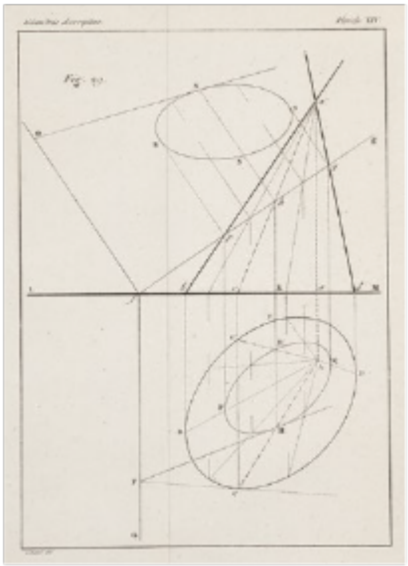
eye has since left an indelible mark on all aspects of Western modernity. But the cultural and technical primacy of modern, perspectival, projected images—and, with that, of images in general—is now drawing to a close. The imminent demise of the image-based visual culture of modernity is all the more inevitable as it is due not to ideology, but to sheer technological obsolescence: Just as during the Renaissance, Western information technologies went from verbal to visual, today global technology and culture are going from visual to spatial—from 2-D to 3-D, from perspectival projection to volumetric point cloud.

RENAISSANCE ARTISTS were keenly aware of the technological novelty of the images they were using, and of the advantages they offered. Painting came to be seen as equal to the written word, even competing with poetry.[4] Painters, who were manual workers and guild members like all others in the Middle Ages, started to be seen as artists, dealing as they were with a new class of high-tech artifacts: perspectival images. But some Renaissance artists were also sculptors, and the competition between painting and sculpture (the "*paragone delle arti*"), or between 2-D and 3-D copies, soon became one of the hottest topics of art theory. The dispute culminated around the mid-sixteenth century, when the Florentine humanist and

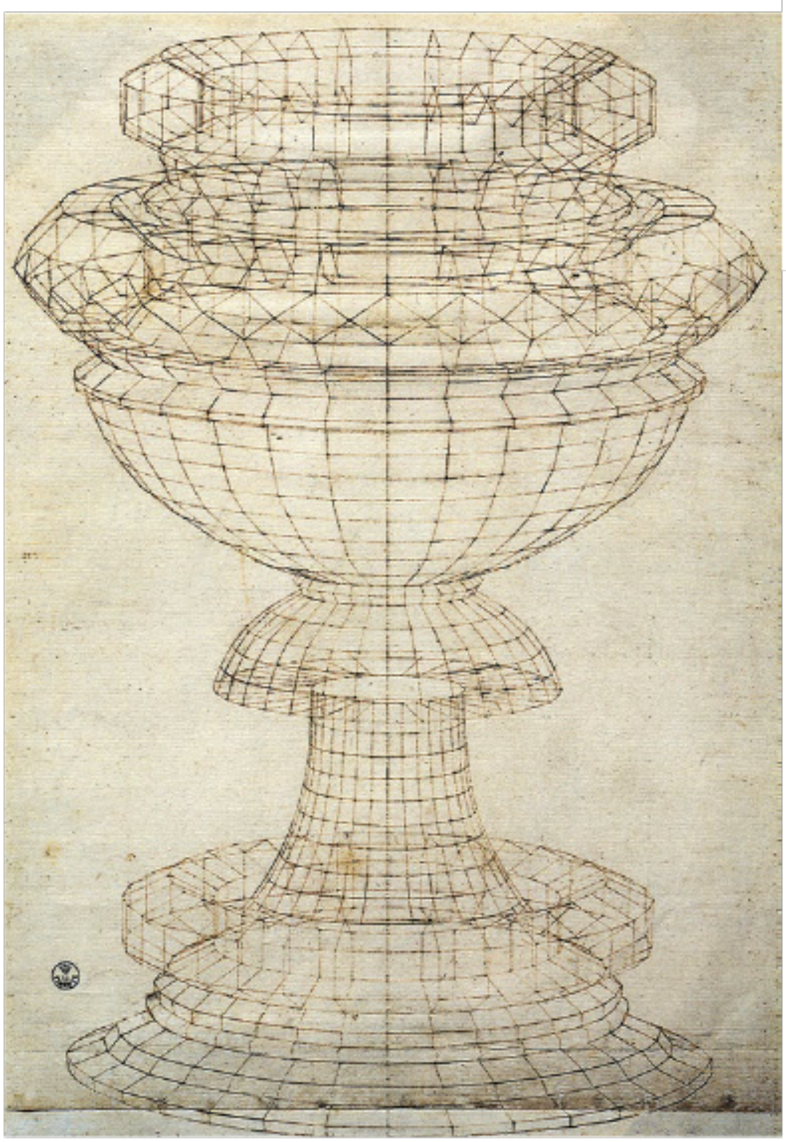
Just as Western information technologies went from verbal to visual during the Renaissance, today global technology and culture are going from visual to spatial—from 2-D to 3-D.

historiographer Benedetto Varchi (1503–1565) posted a call for papers on the subject and published the replies he received in a volume, preceded by his own lengthy essay.[5] Michelangelo, the only contributor Varchi cites on the title page, unsurprisingly championed sculpture. Always a *révolté*, Michelangelo was going against the stream. Almost everyone else in the Renaissance rooted for painting.

The main arguments for the supremacy of painting over sculpture had already been staked by Leonardo da Vinci around 1492.[6] Sculpture is a craft, and sculptors are manual workers, whereas painting is based on the mathematical laws of perspective, hence the painter is a mathematician and a scientist. Sculpture may be closer to reality in a literal sense, but perspectival images do not only represent reality, they also *measure* it. By the way they are made, perspectival images embed the precise proportional measurements of whatever they show, because all they show has been measured by the painter and can be measured again in the painting by each viewer. This is because, in Leonardo's words, "perspective is a very subtle invention and investigation of mathematical studies," based on "laws and demonstrations."[7] In today's terms, the geometry of the perspectival construction is reversible: Alberti's geometric rules convert every point in space, including infinity, into a point of the picture plane, and the other way around—or almost, as in all projections.[8] In short, the main advantage of painting[9] over sculpture is scientific precision: Perspective is a measuring tool—as much a tool of representation as a tool of quantification. Yes, perspectival images also look quite similar to the things



Clockwise, from left: **Page from an 1811 edition of Gaspard Monge's *Géométrie descriptive* (Descriptive Geometry). Components of Evan Kuester's 3-D-printed *K-1* hand, 2015.** In collaboration with e-NABLE Community Foundation and 3D Systems. **Page detail from an 1804 combined edition of Leon Battista Alberti's *Della pittura* and *Della statua*. Paolo Uccello, perspective study of a chalice, ca. 1430–40,** ink on paper, 11⅜ × 9⅝".



we see, but if realism had been the only criterion, sculpture would easily have won the day, as sculpture is much more similar to three-dimensional reality than any planar image can ever hope to be.

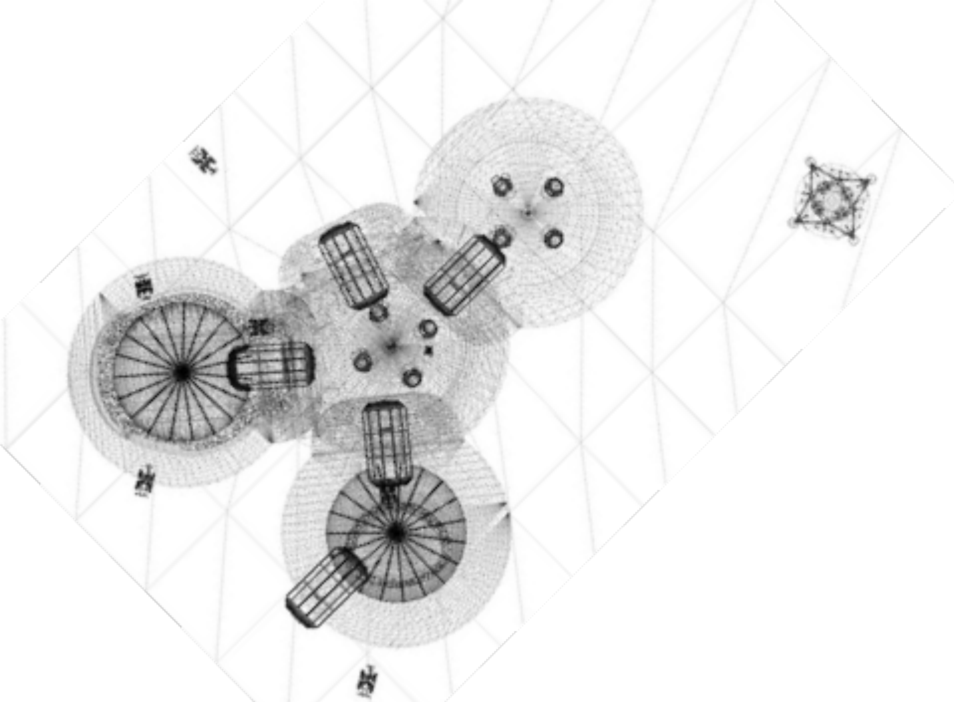
Indeed, even Leonardo had been obliged to admit that sculpture can better represent an object in the round that any single painting can, as sculptures offer views of an object from all vantage points, and a picture is limited to one. Leonardo's counterargument was that two pictures, each composed from a well-chosen vantage point—back and front, for example—can capture enough data to describe any 3-D object in full, but he must have known that that is not always the case.[10] Starting with Lorenzo Lotto, Renaissance painters sometimes provided full identification of their subjects by combining three, not two, views in the same painting. Lotto appears to have rotated his subject by approximately 120 degrees at a time, thus offering a partial view from the back. When Van Dyck was commissioned to create a full-round view of Charles I's head to ship to Rome so that Bernini could make a bust of the king without traveling, he represented the monarch in a neat architectural combination of views: front, side, and at forty-five degrees. Why Philippe de Champaigne, given a similarly utilitarian commission, should have represented Cardinal de Richelieu's bust at a slight angle, and then in two identical specular profiles, is not clear. It even seems somewhat wasteful: Richelieu's prominent nose looks exactly the same when seen from either side.

With the rise of modern science, however, the mensural function of perspectival images was increasingly challenged by other modes of projection better suited to technical notation. From the very start, Alberti had recommended that designers avoid perspective and use instead a kind of nonforeshortened, scaled drawing—similar to what today we would call plans, elevations, and side views in parallel projections.[11] When drawn in this way, all lines parallel to one another are in the same scale—a major advantage for technical and construction drawings. But parallel projections did not exist in the fifteenth century, and plans, elevations, side views, and sections long remained a practice without a mathematical theory: The rules of parallel projection were formalized by French mathematician Gaspard Monge only at the end of the eighteenth century. Monge's method, known as descriptive geometry, uses two sets of parallel projections to univocally notate the position of any point in space onto two planes that, if needed, can be drawn on the same sheet of paper.[12]

Today, the conflation of new technologies for capturing and reproducing reality directly in three dimensions, without the mediation of projected images, is likely to have epochal consequences.

DESCRIPTIVE GEOMETRY is a brilliant mathematical invention, and when it is put to practical use, its efficacy is formidable. No one could "store" a full size skyscraper—say, the Seagram Building—in reality; but many offices could store, in a few drawers, the batch of project drawings necessary to make it and, if needed, to remake it. With parallel projections (including axonometric views, which came a bit later),[13] the art of compressing big 3-D objects onto small, flat sheets of paper (or parchment or canvas or Mylar) reached the apex of modern quantitative precision: Parallel projections do not even try to look like the objects they represent, but aim at recording and transmitting the measurements, place, and shape of a volume in space as precisely as possible—and using as little data as possible. Projections convert volumes (i.e., a number of points equal to infinity to the power of three) into surfaces (a number of points equal to infinity to the power of two). In pure data metrics, one could thus say that the savings are almost infinite—or at least very big. However, such data cheapness is increasingly unwarranted today: Using digital technologies, we can already store not only a huge number of planar drawings but also full 3-D avatars of buildings on a single memory chip—including all the data we need to simulate that building in virtual reality, or to build it in full.

Oddly, even this latest technological leap was anticipated by Alberti himself. In his mid-fifteenth-century treatise *De statua* (On Sculpture), Alberti had introduced a revolutionary 3-D design and fabrication method, entirely based on digital data. Thanks to a



From top: **Foster + Partners and European Space Agency, *Lunar Habitation*, 2012–.** Rendering. **Construction of MX3D's 3-D-printed bridge, Amsterdam, 2015–.** Rendering. **Still from a promotional video for Microsoft HoloLens wearable holographic technology in collaboration with Trimble, 2015.**

peculiar measuring device of his invention (a wheel with a revolving spoke and hanging plumb lines), Alberti claimed that free-standing, solid bodies could be scanned, recorded, transmitted, and replicated, in full or in part, exclusively using numbers—and without any recourse to images.[14] This, however, would have required the manual processing of an extraordinary number of measurements; hence Alberti's precocious CAD/CAM technology immediately fell into oblivion. Several equally unfruitful attempts to develop similar replicating technologies are recorded at the onset of the mechanical age—including one by Samuel F. B. Morse, of telegraph fame. Morse, a noted painter, and later a professor of literature of the arts of design, may have been aware of Alberti's precedent, but his machine was no more successful than his Florentine predecessor's.[15]

Both Alberti's and Morse's technologies would have required a seamless connection between a numerically based scan and a similarly numerically based fabrication process, which no manual or mechanical tool can effectively provide. But today's cheap and increasingly ubiquitous digital 3-D scanners and 3-D printers work exactly that way.

MANY NOW SEE 3-D printing as a turning point in the history of technology. At the same time, however, today's rise of 3-D technologies for scanning and visualization—from the cheap and versatile Microsoft Kinect, hacked by architectural students around the world, to more recent developments in stereoscopic virtual reality—is also likely to change the way we *see* almost everything, and represent and know the world around us. Already, 3-D-printed objects seem poised to take over the role previously played by photographic images in our daily life. The imagemaking technologies we grew up with would typically allow us to take a snapshot of any object—say, a cat—and print it out as a flat, photographic, perspectival picture. But today's technology allows us to snap a scan of the same cat and print that out as a sculpture—life-size, if needed. The French company Photomaton (known for owning and operating thousands of automatic photo booths in public places), for example, recently launched a 3-D photo booth that not only produces traditional pictures but also constructs a volumetric scan of the full figure of the client (a statuette can then be 3-D-printed off-site and shipped to the address provided by the user).[16] Cheap and affordable technologies such as Autodesk's 123D

A replica Nefertiti bust being 3-D-scanned at the Fraunhofer Institute for Computer Graphics Research IGD, Darmstadt, Germany, December 3, 2013. Photo: Boris Roessler/Alamy.

Catch and Google's Tango can already turn out 3-D models of large full-round volumes and of internal spaces, which customers can enrich with the physical data they need for specific purposes;[17] a voxel with added information on the properties of the materials that compose it is often called a maxel, and designers routinely use 3-D models to render geometry and shapes as well as to simulate all kinds of performance (structural, thermal, energy, etc.).

Yet whether produced for highly technical tasks or for general-audience purposes (first and foremost, entertainment and gaming), 3-D models are in fact very seldom printed. Distributed 3-D printing may soon upend global manufacturing, but just as most photographs have long been seen only on electronic displays, today's 3-D models are best navigated in simulations. The first consumer light-field camera, the Lytro, was released in 2012; it was advertised as a camera that allowed customers to refocus and marginally shift the vantage point of each picture *after* the snapshot has been taken.[18] It was not a success, partly due to the limits of light-field technologies for depth sensing, but the implications of its new imagemaking process were vast and momentous: When you take a picture that way, you do not project in onto a screen (the Albertian way) once and for all; you create a 3-D model in space that you can eventually visit at will, looking in different directions and moving around it (in Albertian terms, rotating the central ray and changing the point of view). In 2014, ScanLAB Projects (a spinoff of a research group at the Bartlett School of Architecture in London)[19] recorded an entire Vivienne Westwood fashion shoot as a volumetric point cloud, and in the summer of 2016 various sports events were broadcast live in virtual reality (including some from the Rio Olympics), to be experienced through head-mounted displays. The degree of immersiveness supported by these VR technologies is variable—the vantage point of the end user may be fixed or moving and the angle of rotation of the head more or less wide; the headsets do not have to be stereoscopic, although it helps if they are.[20] Alongside virtual reality, a new generation of head-mounted displays supports augmented-reality and mixed-reality reenactments. In fact, the ways to exploit and experience a 3-D model, once it is made, are countless, and planar images still have many practical advantages over 3-D models: So long as we have eyes to see, we shall keep using monocular images (better if paired and synced for stereoscopy) for all kind of reasons and tasks. But the competitive edge that projected images enjoyed for centuries over 3-D models was due as much to physical as to data lightness. From Alberti until recently, projected images were the best way to capture, notate, and replicate all sorts of 3-D originals, because projections (perspectival or otherwise) compress a lot of spatial information into small and portable planar files—most of the time, as small as a piece of paper. That still holds true, but it matters less and less, because data is now so easy to gather and so cheap to keep and copy. Soon, we shall use our cell phones to take 3-D scans, not photographs.[21] And keeping, editing, sending, navigating, sharing, or even printing a statuary selfie will soon cost the same as keeping, editing, sending, viewing, sharing, or even printing a pictorial one.

At the end of the Middle Ages, the conflation of a new technology for capturing and compressing images and of a new technology for reproducing them changed the history of the West. Today, the conflation of new technologies for capturing and reproducing reality directly in three dimensions, without the mediation of projected images, is likely to have similarly epochal consequences. In the mid-sixteenth century, Jacopo da Pontormo, the lunatic Florentine painter, could claim that while God needed three dimensions to create nature, painters only needed two to re-create it; which, he concluded, "is truly a miraculous, divine artifice."[22] Now we need far less of that artifice, as we can represent and reproduce the world just as it was made—in three dimensions. Both ekphrasis and projective imagemaking were as much a virtue as a practical necessity in times of small data. But those times are over—data is now so cheap and ubiquitous that we no longer need to skimp on it. Alphabetical notation and projected images are data-compression technologies that served us well, but which we no longer need. Three-dimensional models have replaced texts and images as our tools of choice for the notation, replication, representation, and quantification of the physical world around us. Once verbal, then visual, knowledge can now be recorded and transmitted in an entirely new spatial format. □

"Mutations-Créations / Imprimer le monde" is on view at the Centre Pompidou, Paris, through June 19.

MARIO CARPO IS REYNER BANHAM PROFESSOR OF ARCHITECTURAL THEORY AND HISTORY AT THE BARTLETT AT UNIVERSITY COLLEGE LONDON. (SEE CONTRIBUTORS.)

Visit our archive at artforum.com/inprint to read Mario Carpo's article on big data and design (February 2014).

NOTES

tap note to return to text

1. This essay derives in part from a chapter of Mario Carpo's forthcoming book, *The Second Digital Turn: Design Beyond Intelligence* (Cambridge, MA: MIT Press, 2017), to which the reader is referred for full citations, translations from the original sources, and additional biography.

2. Pixels are the smallest uniform tiles in a digitized picture; voxels are the smallest uniform building blocks in a digitized volume.

3. The parallel between the discovery of perspective and the invention of print is as old as Vasari. For some more recent (and controversial) takes on the matter, see William M. Ivins Jr., *Prints and Visual Communication* (Cambridge, MA: Harvard University Press, 1953), 23, 158–80; Friedrich A. Kittler, "Perspective and the Book," trans. Sara Ogger, *Grey Room*, no. 5 (Fall 2001): 38–53. Originally published in German as "*Buch und Perspektive*," in *Perspektiven der Buch- und Kommunikationskultur*, ed. Joachim Knape and Hermann-Arndt Riethmüller (Tübingen, Germany: Osiander, 2000), 19–31.

4. See the Renaissance reinterpretation of Horace's classical topos, "*Ut pictura poesis*" (*Ars Poetica* 361): Rensselaer W. Lee, *Ut Pictura Poesis: The Humanistic Theory of Painting* (New York: W. W. Norton, 1967), 3. Originally published as an article in *Art Bulletin* 22, no. 4 (December 1940): 196–269.

5. Benedetto Varchi, *Due lezzioni di M. Benedetto Varchi* (Florence: Appresso Lorenzo Torrentino Impressor Ducale, 1549). See also Varchi, *Paragone: Rangstreit der Künste*, ed. and trans. Oskar Bätschmann and Tristan Weddingen (Darmstadt, Germany: WBG, 2013).

6. Leonardo da Vinci, *Codex Urbinas Latinus 1270*, 20ff., cited in *Scritti d'arte del Cinquecento*, vol. 1, ed. Paola Barocchi, (Milan: Riccardo Ricciardi, 1971), 475–88. The *Codex Urbinas Latinus 1270* is dated by Carlo Pedretti as ca. 1492 in his *Leonardo da Vinci On Painting: A Lost Book (Libro A)*, (Berkeley: University of California Press, 1964), 178.

7. Ibid., 484–88.

8. All the points on the same visual beam, line, or ray (the line connecting the eye with a point being seen) intersect the picture plane at the same point, hence they translate into a single point of the perspectival projection. The mathematical procedure used to extract actual measurements from a perspectival image, known today as photogrammetry, has been known since at least the early seventeenth century: See Filippo Camerota, "'The Eye of the Sun': Galileo and Pietro Accolti on Orthographic Projections," in *Perspective, Projections & Design: Technologies of Architectural Representation*, ed. Mario Carpo and Frédérique Lemerle (London: Routledge, 2008), 115–25, especially 123.

9. By which everyone in the Renaissance meant "perspectival painting," or the making of perspectival images. That started with Alberti, who never distinguished between projected images and painting: His theory of what we now call geometric perspective is set forth in *On Painting*, where Alberti in fact never used the term *perspective*, as if all images were projections, and all painting perspectival.

10. And indeed he says so elsewhere: See *Codex Urbinas Latinus 1270* in Barocchi, *Scritti d'arte*, 487–9.

11. Carpo, *The Alphabet and the Algorithm* (Cambridge, MA: MIT Press, 2011), 16–20.

12. Gaspard Monge, *Géométrie descriptive* (Paris: Baudouin, 1799).

13. The first rules for drawing what we today call axonometric views were published by the Cambridge scientist and pedagogist William Farish in the early 1820s. See Peter Jeffrey Booker, *A History of Engineering Drawing* (London: Chatto and Windus, 1963), 114–27.

14. Alberti, *De statua*, in Alberti, *On Painting and On Sculpture: The Latin Texts of "De Pictura" and "De Statua,"* ed. and trans. Cecil Grayson (London: Phaidon, 1972), 117–42. *De statua* was composed in Latin at some point between 1435 and 1466. Alberti used a similar number-based technology to scan and copy a map of Rome: See Mario Carpo and Francesco Furlan, eds., *Leon Battista Alberti's Delineation of the City of Rome (Descriptio vrbis Romæ)* (Tempe: Arizona Center for Medieval and Renaissance Texts and Studies, 2007), and Carpo, *The Alphabet and the Algorithm*, in particular section 2.2, "Going Digital," 54–8.

15. *Samuel F. B. Morse: His Letters and Journals—Edited and Supplemented by His Son Edward Lind Morse* (Boston: Houghton Mifflin, 1914), 1, 245; see also the letter of August 22, 1823, with reference to his invention of a "*machine for sculpture*" (247) that would deliver "perfect copies of any model" (245). See also Morse, *Lectures on the Affinity of Painting with the Other Fine Arts*, ed. Nicolai Cikovsky Jr. (Columbia: University of Missouri Press, 1983), 43, 139.

16. "*Cabine 3D*," accessed August 17, 2016, www.photomaton.fr/innovations/cabine_3d.

17. Autodesk 123D home page, accessed March 3, 2016, http://123dapp.com/catch; Tango home page, accessed March 3, 2016, https://get.google.com/tango/.

18. "About Lytro," accessed August 17, 2016, http://lytro.com/about.

19. ScanLAB Projects home page, accessed March 3, 2016, http://scanlabprojects.co.uk.

20. See, for example, Facebook's Oculus Rift, Samsung's Gear VR, or Microsoft's HoloLens.

21. Thanks to technologies such as Autodesk's 123D Catch this is already possible at the time of writing.

22. Jacopo da Pontormo, letter dated February 18, 1546, in Varchi, *Due lezzioni di M. Benedetto Varchi*, 134.

BACK TO TOP