Guido Caldarelli

On Science and Beauty

ARCHiPub. On Cultural and Digital Matters
Published by Fondazione Giorgio Cini 01/002

Guido Caldarelli is Full Professor of Theoretical Physics at Ca' Foscari University of Venice, and a LIMS Fellow. He studied Statistical Physics and has got his degree in 1992 in Rome (La Sapienza), his PhD in 1996 in Trieste (SISSA). After Postdocs in Manchester and Cambridge he became firstly "Research Assistant" in INFM and secondly "Primo Ricercatore" at ISC-CNR where he is still working. From 2012 to 2020 he has been Professor at IMT Lucca. In 2019 he has been one of the founders of SIFS. From 2018 he is the President of the Complex Systems Society and from 2016 he is in the board of the SNP Division of European Physical Society.

Science and beauty are often thought of as being distinct and separate fields, with science concerned with understanding the underlying mathematical mechanisms of the natural world (Copernicus et al. 2003) and beauty typically considered a subjective experience. In actual fact, aesthetics (Guyer 2005) – a branch of philosophy devoted to the study of the beauty (McMahon 1999) and art (Gessert 2008; McMahon 1999) – suggests that some kind of 'beauty' might indeed be objective (Kant 1987) and this is achieved by introducing the distinct categories of 'beauty' and the 'sublime' (Burke 2014) (Doran 2015). Under this respect, it seems reasonable that the connection between these two disciplines might exist albeit a tenuous one. However, the general sentiment of scholars across disciplines is that these two aspects of our world are very closely intertwined. The interaction between science and beauty gives rise to a variety of topics. For example, assuming that art is the procedure by which to 'create' beauty, many people devote their research to:

a. *how to use of art to communicate scientific concepts*: many scientists and science communicators use art as a way to make complex scientific ideas more accessible and engaging to the general public. This can take the form of visual art, such as scientific illustrations or data visualisations, as well as more traditional forms of artistic expression, such as music or dance;

b. the role of beauty in scientific research: some scientists have argued that the pursuit of beauty in science can be a powerful motivator and can lead to more profound insights and discoveries. Others have argued that the pursuit of beauty can be a distraction and that the focus should be on the pursuit of truth and understanding;

c. the use of science to inform the creation of art: many artists use scientific principles and techniques to inform their artistic practices, such as exploiting mathematical models to create intricate patterns or using computer algorithms to generate novel visual effects.

As I cannot discuss all these points here, I shall focus on only one specific aspect.

One typical concept is that of 'the beauty of science': while following Kant's opinion, beauty is not just a matter of personal taste, but, for example, the appreciation of colours is intimately linked to the laws of optics ruling diffraction and the interference of different wavelengths. Admiration for natural regular structures results in a similar appreciation of the principles of biology, chemistry and thermodynamics that gave rise to them. In such a view, science is 'beautiful' because it explains 'beautiful' phenomena. More subtly, and this is the topic of this contribution, there is a particular scientist's conception of beauty related to the mathematical laws behind the phenomena that for some reason are very well rooted in the literature (Breitenbach 2015). In this case, the 'beauty' of nature (for example, but not only) is the result of underlying 'beautiful' scientific principles that govern the behaviour and appearance of these phenomena. (McAllister 1998).

A recent piece of research reporting on the results of a survey amongst researchers about the role of beauty in their activity (Owens 2022) shows particularly clearly what the concept of beauty is for the scientists interviewed. The vast majority (larger for physicists and smaller for biologists) link the beauty of a rule and of a phenomenon (ignoring for the moment what the cause is) to the concepts of symmetry and simplicity. I will focus mainly on these two aspects here.

In science, symmetry is used to describe the property of a system or object that remains unchanged when certain transformations are applied to it. A snowflake is symmetrical because it looks the same when rotated by certain angles. Similarly, a circle is symmetrical because it looks the same when rotated by any angle. As we shall see in detail in the following paragraphs, symmetry is important in science because it allows us to make predictions about how a system will behave (Brading & Castellani 2003).
Unlike the case of 'symmetry', simplicity is not always considered a key element of beauty. In art, simplicity is often associated with the idea of minimalism, which is the use of simple forms and minimal detail in order to create a sense of beauty and balance. In science, simplicity is often associated with the idea of parsimony, which is the principle that the simplest explanation for a phenomenon is the most likely to be true or returning to philosophy to the Occam's razor (Gál & Wood 1991). This principle is often

used in scientific theories, as it allows scientists to make parsimonious hypotheses in their mathematical modelling of the world.

1 SYMMETRY IN PHYSICS

There are many different types of symmetry that are important in physics, including spatial symmetry, temporal symmetry and symmetry under different physical transformations. *Spatial symmetry* refers to the property of a system that remains unchanged when it is rotated or reflected in space. *Temporal symmetry* refers to the property of a system that remains unchanged when it is observed at different times. *Symmetry under different physical transformations* refers to the property of a system that remains unchanged when it is subjected to various physical processes, such as scaling or stretching (fractals [Mandelbrot 2021] remain the same under such transformations).

One major application of symmetry in physics is in the development of physical laws and theories. Many physical laws and theories are based on symmetries, and the symmetries of a system can provide important clues to the underlying principles that govern its behaviour. For example, the laws of thermodynamics are based on the symmetry of energy, which remains unchanged when transformed from one form to another. The theory of relativity is based on the symmetry of space and time, which remain unchanged when an object is moving at a constant velocity.

Symmetry is also important in the study of fundamental particles and forces. The symmetries of these particles and forces can provide important insights into their properties and interactions. For example, the symmetries of the fundamental forces of nature, such as electromagnetism and strong and weak nuclear forces, have been used to develop the standard model of particle physics, which is a theoretical framework that describes the fundamental building blocks of matter and the forces that govern their behaviour.

1.1 THE NOETHER THEOREM

A basic mechanism that shows the role of symmetries in forecasting phenomena was discovered by the female mathematician Emmy Noether ('Emmy Noether – Wikipedia' n.d.). The Noether theorem (Noether 1918) is a fundamental result in physics that relates the symmetries of a physical system to the laws of conservation that govern it (Lederman & Hill 2004). The theorem was developed in 1915, and it has since had a profound impact on the development of modern physics. The Noether theorem states that for every continuous symmetry of a physical system, there is a corresponding law of conservation.[1] For example, if a physical system exhibits spatial symmetry,

1 Conservation laws as for example conservation of energy or conservation of momentum are a powerful ally when we try to forecast phenomena. Whatever happens now, I already know what will be the energy or the momentum in the future. By using these constraints I can determine the evolution laws.

meaning that it remains unchanged when it is rotated or reflected in space, then it must also exhibit a conservation law associated with that symmetry. Similarly, if a physical system exhibits temporal symmetry, meaning that it remains unchanged when it is observed at different times, then it must also exhibit a conservation law associated with that symmetry. By identifying the symmetries of a physical system, we can determine the corresponding conservation laws, which can give us insight into the fundamental principles that govern its behaviour. Once the situation of the system is described by means of its Lagrangian function, $L(\mathbf{q}, \dot{\mathbf{q}}, t)$ that in order to fulfil the principle of minimal action the Lagrange equation must hold,

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} - \frac{\partial L}{\partial q_j} = 0$$

so if the Lagrangian is symmetric with regards to certain transformations, this means that the Lagrangian does not depend on certain coordinates qi. And so this means the above equation may be reduced to:

$$\frac{\partial L}{\partial q} = 0 \rightarrow \frac{d}{dt}\frac{\partial L}{\partial \dot{q}} = 0 \rightarrow \frac{\partial L}{\partial \dot{q}} \equiv p \text{ is constant}$$

For example, the otherwise mysterious (if not mind-blowing) phenomenon of conservation of energy can be explained with the fact that the mathematical equation describing the system lacks an explicit dependence on time, so that its conjugate moment (the energy) is constant.

The Noether theorem has been applied in a variety of contexts in physics, including classical mechanics, quantum mechanics and the theory of relativity. It has also been used to develop new physical theories and to make predictions about the behaviour of physical systems.

1.2 SELF-SIMILAR PHENOMENA IN GEOMETRY

Another kind of symmetry appears when the phenomenon looks the same under changes of scale. Fractals for example have this property and are defined as self-similar objects, meaning that they are made up of smaller copies of themselves. Strangely enough, these kinds of phenomena are much more frequent than one might expect, ranging from natural (Mandelbrot 2021) to social (Zipf 2016) and economic (Pareto 1971) phenomena.

Fractals are often characterised by their intricate patterns and have been used to describe a wide range of natural phenomena, including the shape of coastlines (Mandelbrot 2021), the structure of trees (West, Brown & Enquist 1999), and the distribution of galaxies (Coleman & Pietronero 1992). Fractals are also often considered beautiful, and they have provided a popular subject of artistic expression. The intricate patterns and shapes of fractals can be mesmerising and may evoke a sense of awe and wonder. Many artists have been inspired by fractals and have used them as a basis for their work, creating intricate and detailed pieces that showcase the beauty of these mathematical constructs. Despite the apparent complexity of the structure, the whole

Figure 1. A simple iteration procedure infinitely repeated produces the Sierpinski triangle, a deterministic fractal object.

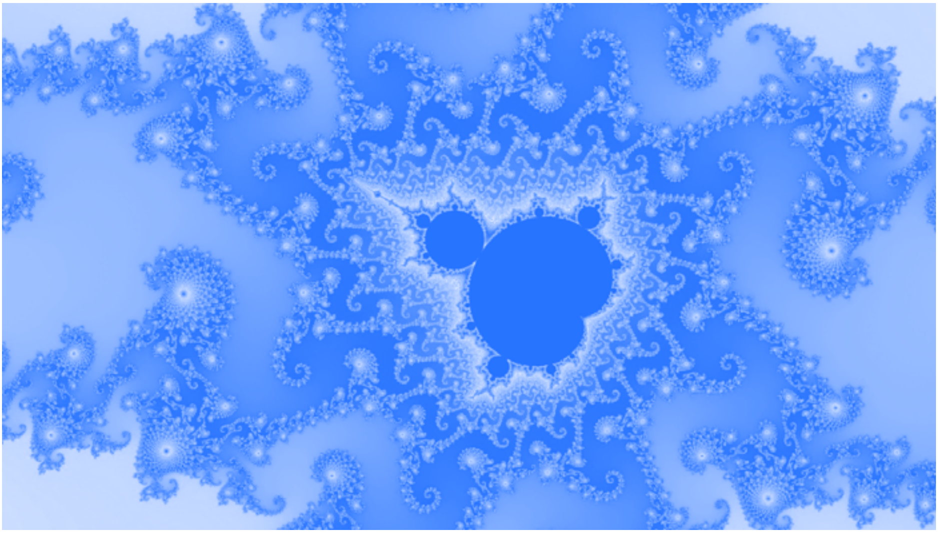

Figure 2. A snapshot of a Mandelbrot set.

set can be produced from a simple equation. The set is formed by the complex numbers c for which the function

$$f_c(z)=z^2+c$$

does not diverge to infinity when iterated from z=0 (You can explore it online on https://math.hws.edu/eck/js/mandelbrot/MB.html). This point brings us directly to the other 'scientific' requirement for beauty: simplicity.

2 SIMPLICITY AND COMPLEXITY IN PHYSICS

Most of the activity in science and ultimately its core – i.e. the scientific method – is related to the reductionist approach. Given the world around us, we must in some way extract a mathematical model describing a part of it, and then verify if such mathematical description is able to explain what we see and forecast future evolution. As long as this works, the model is correct, otherwise it must be modified in accordance with experimental observations. As the analysis goes into the detail of what we observe, we face the complexity of the situation, in the sense that trying to reduce the variables of the phenomenon can be a very difficult task. Complexity emerges when the behaviour of the overall system is not predictable on the basis of the behaviour of the individual elements. We cannot explain the functioning of a brain from the functioning of a neuron; we cannot predict whether a material will be a conductor or an insulator by looking at a single atom of it. This happens because – as stated by the Nobel Laureate Phil Anderson –

"more is different" (Anderson 1972).

In this situation, the only way to reduce the complexity of the phenomenon is to find a parsimonious way to represent the many constituents and their relation with each other. Complex networks (Caldarelli 2007) are a type of mathematical structure that is used to describe and analyse the relationships between various elements or nodes within a system. Complex networks are characterised by their intricate and often beautiful patterns, and they have been used to model a wide range of systems, starting from the internet shown in Figure 3 (image from Internet Mapping Project) but also including social networks (Vega-Redondo 2007), and biological systems (Buchanan et al. 2010). Consequently, they have been used to study a variety of issues ranging from the spread of diseases (Pastor-Satorras & Vespignani 2001), to the stability of interbank credits (Bardoscia et al. 2021), and propagation of disinformation (Lazer et al. 2018), among other things.

This property gives complex networks the ability to capture the complexity and interconnectedness of real-world systems in a way that simpler models cannot. Their patterns can reveal key insights about the underlying principles that govern the behaviour of the system, and they can be aesthetically pleasing to look at. Many researchers and some artists have been inspired by the beauty of complex networks, and have used them as a basis for their work.

Overall, the beauty of complex networks lies in their ability to capture the complexity and interconnectedness of real-world systems in a way that is both aesthetically

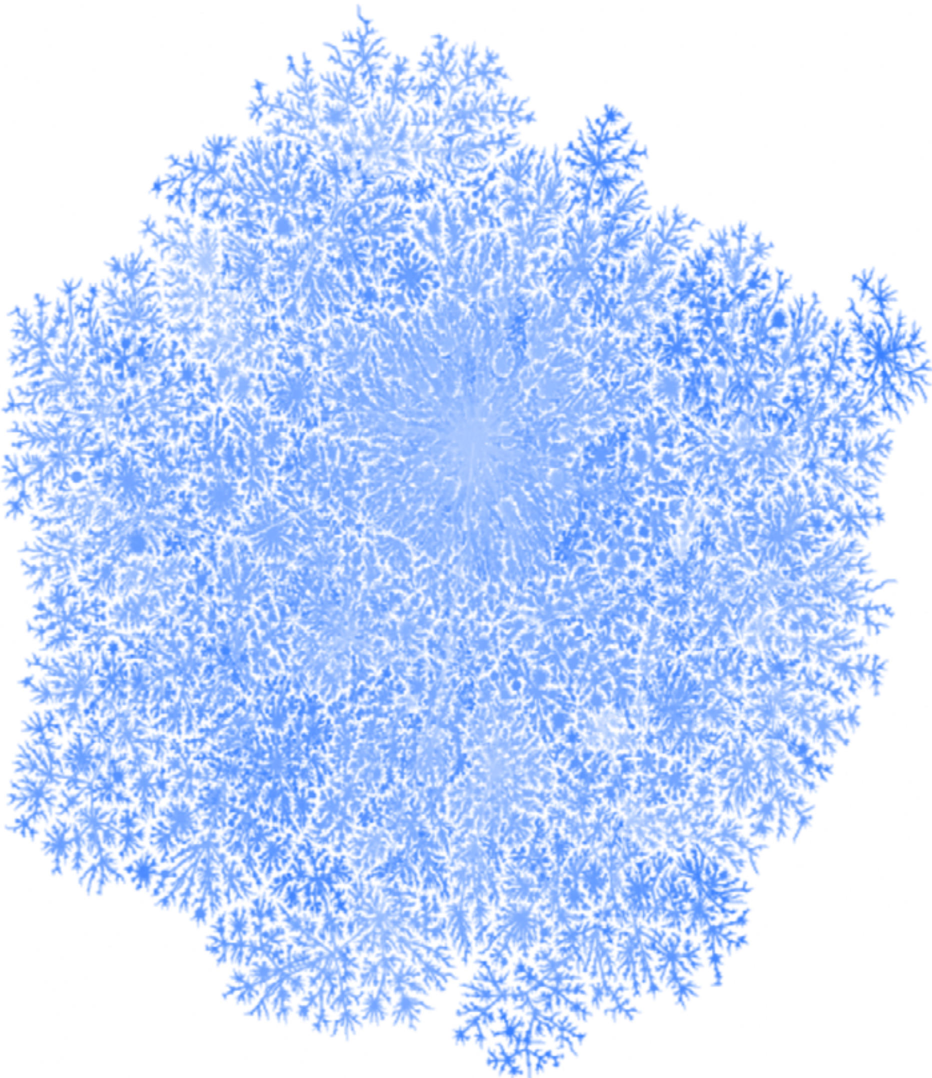

Figure 3. A representation of internet connections: every point is an autonomous system and the link is a physical connection between them.

pleasing and scientifically useful. In particular, the geometry of complex networks allows us to define a measurement of distance between entities even in the absence of metrical spaces.

Questions like “how similar are two people?” “how similar are two texts?” “how similar are two artists?” have no quantitative answers. Nevertheless, the use of complex network and the abundance of data makes possible to make various proxies of these quantities (Fraiberger et al. 2018). A particularly interesting application is that of archival data, where networks allow us to understand the structure of archives themselves as well as to visualise the content of archival corpora.

3 THE FUTURE AND BIG DATA

As contemporary society is becoming more and more interconnected and larger, we must expect these large numbers to affect both science and art and possibly also change the concept of beauty we are used to (while probably leaving the ‘sublime’ category unaffected). ‘Dataism’ is a term coined by Hungarian-American physicist and network scientist Albert-László Barabási in his book *The Formula: The Universal Laws of Success* (Barabási 2018). In his book, Barabási discusses the increasing importance of data and the ways data is driving the development of new technologies and shaping our understanding of the world. According to Barabási, dataism is a worldview that sees data as the most fundamental building block of reality. Dataism posits that all aspects of the universe, including biological

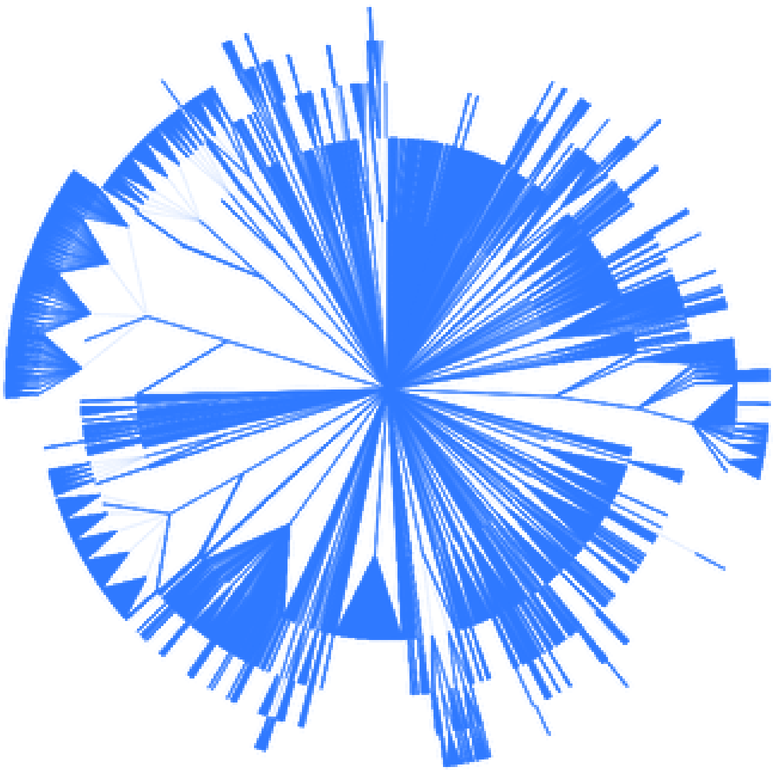

Figure 4. The structure of the State Archive of Venice.

systems, can be understood and explained in terms of data and the patterns and connections that exist within them. Dataism also suggests that the increasing amount of data being generated and collected will allow us to make more accurate predictions about the future and develop more effective solutions to complex problems.

Barabási argues that dataism represents a fundamental shift in our understanding of the world, similar to the shift that occurred with the development of the scientific method in the seventeenth century. He suggests that dataism will have a profound impact on a wide range of fields, including science, technology, business and society at large.

However, Barabási also notes that dataism raises a number of ethical and philosophical questions, such as the potential for data to be used for nefarious purposes or to further widen existing inequalities. He suggests that these issues will need to be carefully considered as dataism continues to shape our world.

Bibliography

- Anderson, P W. 1972. ‘More Is Different’, Science 177 (4047): 393–96 https://doi.org/10.1126/science.177.4047.393
- Barabási, Albert-László. 2018. The Formula: The Five Laws Behind Why We Succeed or Fail. Macmillan
- Bardoscia, Marco, Paolo Barucca, Stefano Battiston, Fabio Caccioli, Giulio Cimini, Diego Garlaschelli, Fabio Saracco, Tiziano Squartini and Guido Caldarelli. 2021. “The Physics of Financial Networks.” Nature Reviews Physics, June. https://doi.org/10.1038/s42254-021-00322-5
- Brading, Katherine and Elena Castellani. 2003. Symmetries in Physics: Philosophical Reflections. Cambridge University Press
- Breitenbach, Angela. 2015. ‘Beauty in Proofs: Kant on Aesthetics in Mathematics’, European Journal of Philosophy 23 (4): 955–77. https://doi.org/10.1111/ejop.12021
- Buchanan, Mark, Guido Caldarelli, Paolo De Los Rios, Francesco Rao and Michele Vendruscolo (eds.) 2010. Networks in Cell Biology. Cambridge University Press. https://doi.org/10.1017/CBO9780511845086
- Burke, Edmund. 2014. A Philosophical Enquiry into the Origin of Our Ideas of the Sublime and Beautiful: with an Introductory Discourse Concerning Taste; and Several Other Additions. Cambridge: Cambridge University Press. https://doi.org/10.1017/

CBO9781107360495
- Caldarelli, Guido. 2007. Scale-Free Networks: Complex Webs in Nature and Technology (Oxford Finance Series). New Edition. Oxford: Oxford University Press
- Coleman, Paul H. and Luciano Pietronero. 1992. “The Fractal Structure of the Universe.” Physics Reports 213 (6): 311–89.
- Copernicus, Nicolaus, Johannes Kepler, Galileo Galilei, Isaac Newton, Albert Einstein and Stephen Hawking. 2003. On The Shoulders Of Giants. Illustrated. Running Press Adult
- Doran, Robert. 2015. The Theory of the Sublime from Longinus to Kant. Cambridge University Press. https://doi.org/10.1017/CBO9781316182017
- ‘Emmy Noether – Wikipedia.’ n.d. accessed 10 January 2023. https://en.wikipedia.org/wiki/Emmy_Noether
- Fraiberger, Samuel P, Roberta Sinatra, Magnus Resch, Christoph Riedl and Albert-László Barabási. 2018. “Quantifying Reputation and Success in Art.” Science 362 (6416): 825–29. https://doi.org/10.1126/science.aau7224
- Gál, Gedeon and Rega Wood. 1991. ‘THE OCKHAM EDITION: WILLIAM OF OCKHAM’S “‘OPERA PHILOSOPHICA ET THEOLOGICA”’. Franciscan Studies 51: 83–101. http://www.jstor.org/stable/41975136
- Gessert, George. 2008. Unnatural Wonders: Essays from the Gap Between Art and Life by Arthur C. Danto.

Farrar, Straus, Giroux, New York, NY, U.S.A., 2005. 400 pp. Trade. ISBN: 0-374-28118-1. Leonardo 41 (4): 402–3. https://doi.org/10.1162/leon.2008.41.4.402

- Guyer, Paul. 2005. Values of Beauty: Historical Essays in Aesthetics. Cambridge, UK: Cambridge University Press
- Kant, Immanuel. 1987. Critique of Judgment (Hackett Classics). 1st ed. Indianapolis, Ind: Hackett Publishing
- Lazer, David M. J., Matthew A. Baum, Yochai Benkler, Adam J Berinsky, Kelly M Greenhill, Filippo Menczer, Miriam J Metzger et al. 2018. 'The Science of Fake News'. Science 359 (6380): 1094–96. https://doi.org/10.1126/science.aao2998
- Lederman, Leon M. and Christopher T. Hill. 2004. Symmetry and the Beautiful Universe. Amherst, NY: Prometheus Books
- Mandelbrot, Benoit B. 2021. The Fractal Geometry of Nature. Echo Point Books & Media, LLC
- McAllister, James W. 1998. 'Is Beauty a Sign of Truth in Scientific Theories? Why Are Some New Theories Embraced as Beautiful, Others Spurned as Ugly? Progress in Science May Require That Aesthetic Ideals Themselves Change.' American Scientist 86 (2): 174–83. http://www.jstor.org/stable/27856983
- McMahon, Jennifer A. 1999. 'Towards a Unified Theory of Beauty'. Literature & Aesthetics 9: 7–27
- Noether, E. 1918. "Invariante Variationsprobleme." Nachrichten von Der Gesellschaft Der Wissenschaften

Zu Göttingen, Mathematisch-Physikalische Klasse 1918: 235–57

- Owens, Brian. 2022. 'Beauty and Wonder of Science Boosts Researchers' Well-Being.' Nature, March. https://doi.org/10.1038/d41586-022-00762-8
- Pareto, Vilfredo. 1971. Manual of Political Economy. Reprint (New English trans.). New York: Augustus M. Kelley, Publishers
- Pastor-Satorras, R and A Vespignani. 2001. 'Epidemic Spreading in Scale-Free Networks.' Physical Review Letters 86 (14): 3200–3203. https://doi.org/10.1103/PhysRevLett.86.3200.
- Vega-Redondo, Fernando. 2007. Complex Social Networks. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511804052.
- West, Geoffrey B., James H. Brown and Brian J. Enquist. 1999. 'A General Model for the Structure and Allometry of Plant Vascular Systems.' Nature 400 (6745): 664–67. https://doi.org/10.1038/23251
- Zipf, George Kingsley. 2016. Human Behavior and the Principle of Least Effort: An Introduction to Human Ecology. Ravenio Books

ARCHiPub
On Cultural
and Digital Matters

EDITOR IN CHIEF
Chiara Casarin

MANAGING EDITOR
Claudio Piscopo

FOCUS RESEARCH 01
Venice Material

VOL. 002
On Science and Beauty

CONTRIBUTOR
Guido Caldarelli

ARCHiVe
Analysis and Recording
of Cultural Heritage in Venice

is a project by
Fondazione Giorgio Cini
Factum Foundation
EPFL – Digital Humanities Laboratory

Supporting funder
The Helen Hamlyn Trust

FONDAZIONE GIORGIO CINI

PRESIDENT
Giovanni Bazoli

SECRETARY GENERAL
Renata Codello

CULTURAL DEVELOPMENT
AND COMMUNICATION
Chiara Casarin
Claudio Piscopo

EDITORIAL OFFICE
Giovanna Pesaro

Publisher
Fondazione Giorgio Cini Onlus
Island of San Giorgio Maggiore, Venice

ARCHiVe
Analysis and Recording
of Cultural Heritage in Venice

ARCHiPub. On Cultural and Digital Matters is an interdisciplinary book series that gathers research on topics such as archival studies, digitisation projects, and cultural heritage conservation. Each volume focuses on a research theme, to be explored by authors from different academic backgrounds.

This contribution is part of the focus research *Venice Material*. Venice Material is the starting point. Venice as a city, as an environment in which history has formed the present civilization and as a fertile humus of ever-new cultural sap. Venice as a bridge between worlds that were sometimes created, sometimes destroyed and still a bridge between ways of producing culture as a primary good. Venice is made out of matter, stone, painting, poetry, a rich and sensitive work, layered materially and immaterially like no other city in the world. Venice as a launching pad for new experimental horizons, as a landing place for new generations of scientists and creative people. But Venice is also considered as a subject of study, a focus of scientific and humanistic research, endowed with the persuasive force of authentic insights that seem to multiply rather than run out. Venice as an object to be investigated, disassembled and reconstructed, digitized and disseminated, curated.

fondazione Giorgio Cini onlus