RENAISSANCE SCIENCE

Leonardo's laboratory: studies in flow

On the 500th anniversary of the Renaissance icon's death, **Martin Kemp** looks anew at his innovative experimental models for the motion of water and blood.

Leonardo da Vinci (1452–1519) was a man before his time: we know the cliché. However, in crucial respects he was very much a man of his time. His versatility was foreshadowed by the great artist-engineers of the Italian Renaissance. Notably, Filippo Brunelleschi, inventor and architect of the massive dome of Florence Cathedral, formulated the science of linear perspective for painters in the early years of the fifteenth century. In his work on physical sciences, Leonardo was heir to medieval theories of statics and dynamics; Isaac Newton was still far away. Leonardo's anatomical researches merged medieval physiology with the functional and morphological analyses of the classical physician Galen.

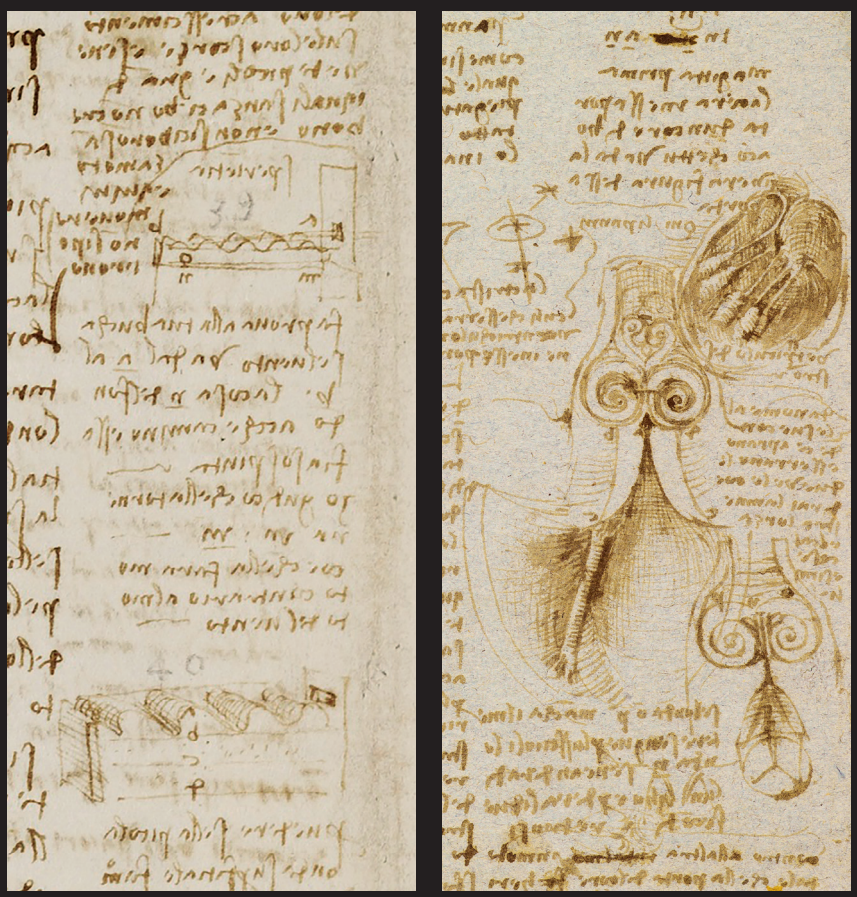
It is better to say that Leonardo's innovations show that he realized more than his predecessors or contemporaries managed to do in the scientific context of his period.

The most conspicuous of Leonardo's innovations is his perfection or invention of almost all the illustrative techniques known before the X-ray. In his notebooks, he depicted subjects using perspective; showed solid forms modelled systematically in light and shade; sectioned them to reveal their inner structures; used transparency to show underlying features; portrayed 'exploded' views of body and machine parts to disclose their forms and articulations; invented diagrammatic representations to disclose the functions of bodily and mechanical systems; and drew thought experiments to explore how things worked. He deployed these techniques widely across his scientific and technical endeavours.

FLUID MOTION

Among the vast range of phenomena that Leonardo explored and depicted was the behaviour of liquids. Now, in *Leonardo da Vinci's Codex Leicester* — a new four-volume edition of the 72-page scientific notebook, composed after 1508 — science historian Domenico Laurenza and I show how his revolutionary ideas on fluid dynamics operated in the specific context of the ancient history of the 'body of the world'.

The outer pages of the codex deal in part with Leonardo's theories on the passage of light from the Sun to Earth and the Moon, involving reflections from seas real or putative. Most of the notebook, however, is devoted to the study of water in motion, in seas, rivers and canals in the form of *vene*



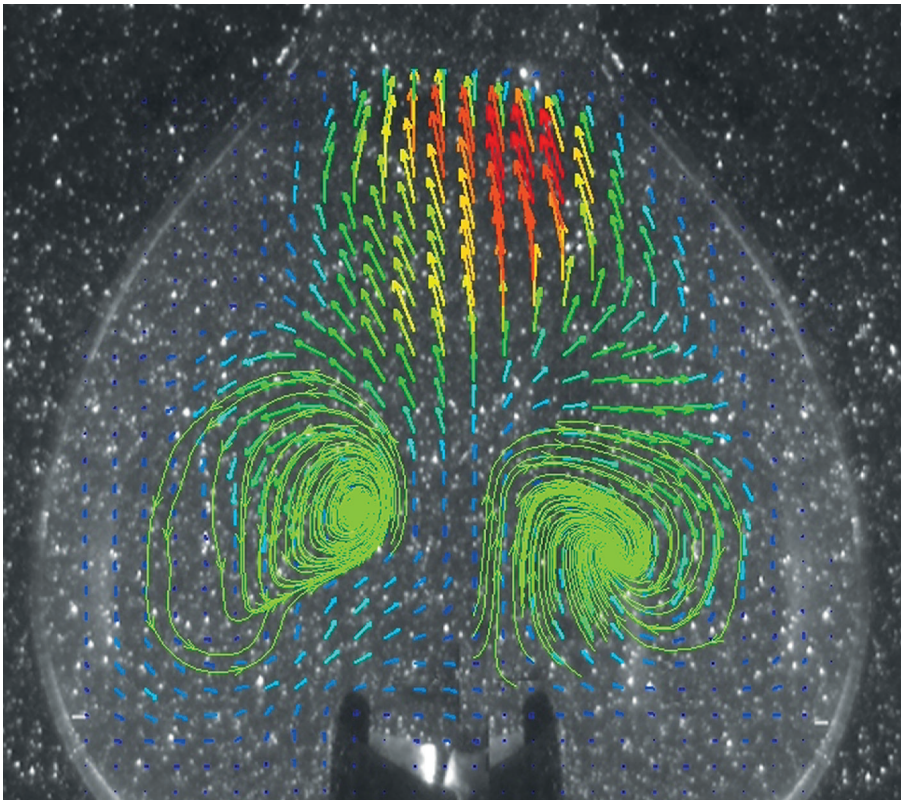
Left: Leonardo da Vinci's sketches of experimental tanks for studying waves and currents in water. Right: Sketches exploring Leonardo's theories about vortices in heart valves.

LEFT: COLLECTION OF BILL GATES, SEATTLE/PHOTO: BILL GATES; RIGHT: LEONARDO DA VINCI, *STUDIES OF BLOOD IN AN AORTIC VALVE AND A GLASS MODEL OF THE NECK OF AN AORTA*, WINDSOR CASTLE, ROYAL COLLECTION TRUST/© HER MAJESTY QUEEN ELIZABETH II 2019

Studies of Turbulent Water **shows Leonardo's understanding of how vortices move.**

LEONARDO DA VINCI, *STUDIES OF TURBULENT WATER*, ROYAL COLLECTION TRUST/© HER MAJESTY QUEEN ELIZABETH II 2019

MORY GHARIB AND ARASH KHERADVAR



A model showing vortices that close a heart's aortic valve, built by Morteza Gharib to Leonardo's design.

d'aqua (veins of water), on Earth's surface and underground. The principle underlying Leonardo's thinking is that of the micro- and macrocosm: he saw the human body as a 'lesser world', mirroring the forms and functions of the wider world.

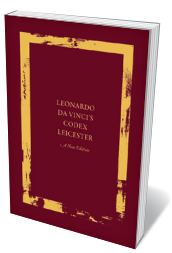
Whereas earlier authorities, such as the second-century Roman astronomer and geographer Ptolemy, had seen Earth as undergoing relatively local changes, Leonardo saw it as having an ancient life-story of vast transformations. In his geological theories, sections of Earth's crust collapsed, violently transforming the relationship between earth and water. As centres of gravity shifted, portions of crust extruded to form lands and mountains.

As Laurenza and I reveal, among the most original aspects of his investigation are what may legitimately be called 'laboratory experiments' using ingenious physical models. Leonardo's extended analyses of the behaviour of water combine mathematical theories of motion with acute observation. The experiments documented in the codex were designed to show how waves are generated by wind, and how currents and vortices perform their complex arabesques under the surface. He sketched an experimental tank in two small drawings in the margins of folio 9v (r denotes the front and v the back of the pages, or folios, of Leonardo's notebooks). The upper drawing is labelled *experientia* ('experience' or 'experiment'). An accompanying note reminds Leonardo "to get a terracotta trough, with a large and flat bottom, 2 braccia [116 centimetres] long and half a braccio [29 cm] wide; have it made here, by the ceramicist". The sides of the tank, he wrote, should be made of glass; he would infuse the water with seeds of panic grass (*Panicum* spp.) that he could use to track the vortices in action.

VALVES AND VORTICES

One of the tasks he set himself was to observe what happens to a mobile object at the bottom of the tank when a current of air is blown through a rectangular opening at one end, just above the water's surface. He decided that the object would move in an opposite direction from the wind.

The experimental set-ups reveal that Leonardo's magnificent studies of turbulence, kept in the Royal Library at Windsor Castle, UK, stem not from observation in nature but from experiments on vortex motions. Concentrating in turn on various aspects of compound action in the motion of water and submerged air, he completed a great synthesis.



Leonardo da Vinci's Codex Leicester: A New Edition (Volume 1)
DOMENICO LAURENZA & MARTIN KEMP
Oxford University Press (2019)

There is more. On folio 15r Leonardo notes that at the junction of two rivers, "what happens with the beds … can be demonstrated with a simple experiment using sand". This laboratory modelling of water interacting with its sandy bed is taken to a higher level of complexity in the Codex Atlanticus, a series of notebooks held in the Ambrosia Library in Milan, Italy. Here, on folio 227v, he proposes to make a proportionally scaled experimental model (*la sperienza nelle minute dimostrazione*) of the gulfs and seas in the Mediterranean, with the major rivers, to test his reconstruction of ancient geological processes. He speculated that the Strait of Gibraltar would widen over time, allowing the Mediterranean to become a mighty river, an extension of the Nile.

Leonardo's studies of the motion of blood in the human body involved similar experimental modelling. He was particularly interested in the heart's passive, three-cusp aortic valve, which he realized must be operated by the motion of blood. To demonstrate his theory that vortices curl back to fill the cusps in the flask-shaped constriction at the aorta's neck, he proposed to make a ceramic mould in the shape of the neck, in which he could blow a glass vessel. He would thus be able to witness (again, courtesy of grass seed) the motion of water and the action of cusps, as a 'proof' of how blood behaves (illustration). Leonardo's model has been constructed by fluid-dynamics specialist Morteza Gharib, who used modern imaging techniques to demonstrate the existence of the revolving vortices that Leonardo interpreted as closing the valve.

Such modelling was hugely original for the early Renaissance. Thus, although Leonardo resided in his own time, he did have some footholds in the future.

It is often claimed that because Leonardo's science was unpublished and uncirculated for centuries, it had no impact on scientific developments. In our edition of the Codex Leicester, Laurenza reveals that the work was in fact available in the circles of those who reformed geology between the seventeenth and nineteenth centuries, such as the volcanologist William Hamilton, British ambassador to Naples from 1764 to 1800. Handwritten copies of the codex enjoyed wide circulation in key places for modern geology: London, Rome, Florence, Naples, Paris and Weimar.

Leonardo always surprises those who study him. ■

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