Experimenta Nova

Magdeburgica de

Vacuo Spatio

by

Otto von Guericke

1672

Joseph Muscat

28 Dec 2022

Otto von Guericke was a 17th century engineer who became a councillor and ambassador for Magdeburg following its destruction. He achieved fame with his experiments demonstrating vacuum. Together with the telescope and microscope, his vacuum experiments transformed natural philosophy in the 17th century, spurring questions about how planets move in empty space, attracted by some mysterious force. Although Robert Boyle and Robert Hooke are too often depicted as having invented the air-pump, or discovered the vacuum[1], it was in fact von Guericke who had already made most of these experiments, with few exceptions. Additionally he pioneered the study of electrostatic attraction and repulsion. This article is an abridged summary of Books 2, 3, and 4 in [1]; for an English translation, see [2].

[1]For example: To quote "The importance of this [Boyle's] book was that it described the first controlled experiments of the effects of reducing the pressure of the air." in John B. West's "Robert Boyle's landmark book of 1660 with the first experiments on rarified air" in Appl. Physiol. 98: 3139, 2005; doi:10.1152/japplphysiol.00759.2004.

Book 2[2]
Empty Space

Chapter I The Author's Reason to investigate Vacuum

From Book I it was found that celestial distances to the Sun, Moon, and Planets, are enormous, up to hundreds the size of the Earth. The stars are even farther away; even if they had just a $2''$ parallax, that would make them 103448 Earth semi-diameters [radii] away. The telescope has uncovered innumerably more stars than can be seen with the naked eye, and it is not to be doubted that many of them are larger than the Sun. It is beyond humans to comprehend the intimidating vastness of the Universe. Yet I was filled with a desire to study this empty expanse. I wanted to investigate whether a vacuum was truly to be denied as the Aristotelians say, or whether it is some sort of fluid aether like the Copernicans say.

Chapter II Space and Time

Philosophers define a vacuum as space with nothing in it. Aristotle defines space as the containing surface of things. What is place? One can say I'm in some room, which is in some house, in some street, etc., until we ask where is Earth, or where is the Sun? Copernicus answers "In the middle of the Universe"; but where is the Universe? Place is always relative to something else, it is not a real thing. Neither is time. Aristotelians define it as a measure of motion, relative to 'before' and 'after'. In my opinion it is a measure of duration relative to the Earth's period around the Sun or its daily rotation. Other planets have their own measure of time.

Chapter III Vacuum

For Aristotle, vacuum is space not filled by matter, but he argues that it cannot exist. According to him, what doesn't cause anything [is not observable] cannot be said to exist. Vacuum, being nothing, cannot cause anything and so cannot exist. However, in response, it is still capable of being filled, and so it is at least something which has an effect. It allows an object to move into the adjoining space. Experiments will show water rushing in to fill a vacuum, but if a vacuum does not exist, where is it rushing to? So to turn the argument around, since vacuum causes "vacuum fugae", it must exist. Indeed, there were philosophers such as Leucippus and Democritus, who accepted vacuum; the Stoics accepted it beyond the Heavens. Among the recents, Descartes also denies the vacuum, for he says, if one removes everything in a container, one removes the distance between the sides and so they would touch. Scaliger answered the question

[2] Book 1 is a description of the Copernican system. Book 5 describes physically the Earth, atmosphere, and Moon. Books 6 and 7 are a brief description of his model of the universe.

"Can God create a vacuum?" by 'No', since it is the opposite of creation. Some point out that daily experience teaches that there can be no vacuum: water sucked up a straw, a blocked bellows cannot be opened, water is held up in an inverted flask, etc. However, experiments will show that vacuum does exist. In my opinion, it is the absence of matter, just as dark is the absence of light and death the absence of life. Though vacuum by itself means 'nothing', vacuous Space is the container of all things.

Chapter IV Space

What is this space cleansed of all its matter? It does not have length or volume. It is a continuum, permanent, indivisible, permeating all objects, the space they need to exist, and to be perceived. Imagine the air taken out of a room; what remains is its space. There is a big difference between empty space and the space that a body takes up. Descartes is wrong when he states that removing the air from a container destroys its dimensions. If one imagines all the air on Earth gone, there would still be distance between mountains.

Chapter V The Space between Heavenly Bodies

We have mentioned in Chapter I the vastness between these bodies. The word Heaven is used in many senses. It is used for, 1. the Atmo-sphere, where reside the clouds, as when we say "it rains from heaven". 2. The sphere of the planets in their orbits. 3. Then the sphere of Stars. 4. The crystalline spheres. 5. The Primo Mobili. 6. Finally the Empyrean Heaven of the blessed. In my opinion, Heaven is a relative term. If we were to remove the Earth, its heavens, that is the range of its potencies, would also disappear, but the space that it takes would remain. But what I call vacuum is not the intrinsic space occupied by the planet but the extrinsic space surrounding it. More properly speaking it is the space external to the atmosphere. From the place of Saturn, the Earth would be visible in its 'heaven'. It is one continuum reaching out to the stars. Does it consist of matter? Planetary spheres cannot be solid, as some astronomers dream, because comets move in between orbits. If it is material, it is of the rarest, invisible, fluid type. Tycho doubted whether this aether is material, and Kepler thought it is empty; I agree.

Chapter VI Whether Universal Space is Finite or Infinite

According to Aristotle, beyond the Heavens there is nothing, neither position nor time since it is everywhere the same and constant, and neither can there be a vacuum made up of nothing. If God is outside this Universe, then He is this Space, immeasurably large in His very nature, as the Jesuit Lessius maintained. But to be able to create something one must first create its container, in order to allow movement. Descartes thinks even matter is infinite in extent, but this is blasphemous because only God is limitless. So, is the Universe finite? Suppose it is and imagine one is at the boundary. Either you can extend an arm further out, or there is a hard obstacle. But how can nothingness resist anything? Thus there is nothing outside the World but a true imaginary empty Space, infinite in extent in all directions. One can never be sure, but can only imagine it, just as one imagines exotic animals.

Chapter VII On what exists, and what does not

Anything that exists is either created or not. What is uncreated must, in its essence, be infinite, eternal, and self-subsisting. What is created owes its existence to the Uncreated; it must be finite and subtantial, from which come all its qualities: quantity, quality, number, etc. Nothingness is unintelligible because it is neither one nor the other; some say a chimera is nothing, but even it is at least a mental image. Outside the World can only be one of these two, and clearly it must be the uncreated. If one asks: What was there before the World? One can answer, either the Uncreated or the Nothing, and both are correct, if by nothing is meant no created thing, just as we say that the Earth was created from nothing, that is, from the Uncreated. 'Nothing' is more precious than gold: it has no beginning nor end, it is everywhere.

Chapter VIII Is Space, the Universal Container, created or uncreated?

Several theologians, among them du Bois of Leyden and Fr Kircher, say that God resides in the infinite space, for He is limitless. It is also agreed by all that nothingness cannot surround God, for then he is constrained by it. Hence it must be admitted that the nothingness surrounding the Universe is God. For He who created the world, contains it and carries it. But according to Aristotle, space is uncreated. Space is not nothing — it is filled with God, including the world which is as nothing to the vastness of space.

Chapter IX The Infinite, the Immeasurable, and the Eternal

Philosophers define the Infinite as that which cannot be exhausted, the Immeasurable in extent as that which has no end in any direction, and the Eternal as time which has no beginning nor end. Age is infinite time that has a beginning. The infinite is not something that can be grasped or described by a number. Any number is finite, since one can always add to it. The infinite, however, cannot be grasped by man. If one moves thousands of miles in space, it is like he hasn't moved at all. One cannot make comparisons of the infinite as if it were a number. If God created a cosmic body along a line for every thousand miles, there would be an infinite number of them; then if each second body is removed, there would still be an infinite number, even if one does this repeatedly.

Chapter X Number

Although it is a common saying that the sands of the shore cannot be counted, yet Archimedes put a number not just to this but to all the grains of the Earth, as follows: 1. Suppose that a poppy seed consists of 10 000 fine grains of sand. 2. Suppose 40 poppy seeds in a line make a finger. 3. 10 fingers make a foot. 4. 5 feet make a step. 5. 10 000 steps make a Germanic mile. 6. Suppose Earth's diameter is 10 000 miles. Then Earth's diameter would be 100 000 000 steps, or 200 000 000 000 poppy seeds. Taking the cubic proportion and multiplying by 10 000 gives that the Earth would contain 80 000 000 000 000 000 000 000 000 000 000 000 000 sand grains. Now, using Ptolemy's model, let us suppose that the sphere of the stars has a diameter less than 50 000 Earth diameters. Taking the cube of this gives a ratio of 1 to 125 000 000 000 000. So, the entire Universe would have a number with 52 zeros, of sand grains, a number so large it is beyond our comprehension. These are large numbers, but with arithmetic one can easily get much larger numbers. A calculator took up my wager of a hundred thalers to start with 2 and to keep squaring it for twenty times within three months. So 4, 16, 256, etc. After just six steps one gets a number with 20 zeros; each squaring doubles the number of zeros, so after twenty steps one gets 327 680 zeros. Oh, poor us, how can we possibly comprehend the infinite Uncreated, when we struggle with these numbers.

Chapter XI Heaven, the Place of the Blessed

It is certain that at the end of the World, everyone is taken to account and taken to Heaven or Hell. But where are they? Since space is infinite, there is no near or far, so Heaven's place can only be compared relative to something else. We commonly say that God resides in the highest Heaven, as we do every Sunday in the Prayer. But in the last Judgement, the sky and Earth will be destroyed, and each cosmic body will have its heaven. Perhaps it will be in the same place that Earth would have been in when it is destroyed or transformed. Is it large enough? We know that Mars is distant from the Sun at 3 739 Earth radii, so the volume enclosed by its orbit would contain 52 271 672 419 Earth globes, and if one removes the sphere enclosed by Venus then 43 669 148 770. That seems to be enough for all the men that ever lived.

Chapter XII Maxima and Minima

Quantity, such as large or small, long or short, etc., is not an absolute but a relative comparison. The created cannot be infinitely large or infinitely small. Only infinity does not admit comparison. So finite bodies, when compared with each other, have a maximum and minimum size, e.g. a planet with the other planets; on Earth, the animals range from the largest, whales or elephants, to the smallest, mites and lice. Objects go down to the minutest things like sand grains and powders, but not to infinity. The smallest limit would be the atoms.

The microscope has uncovered the hidden world of the smallest things, but it still has not uncovered the parts that make air or liquids. Yet nothing is so small that space has not infinitely smaller parts still.

Book 3
The Experiments

Chapter I The Origin, Nature, and Quality of Air

We first consider Air to better understand the subsequent experiments. Air is not an element but a breath that comes out of water, earth, and other humid bodies. This is most evident during putrefaction. Air itself has no smell because we have been accustomed to it since birth. It is capable of expanding itself until very thin. The heat of the Sun or fire evaporates and disperses moisture in the air, which then condenses back again into water. In winter, one can sometimes see the scintillations of atoms frozen out of the air, but air itself never freezes. Hot air occupies more space without becoming rarer; when it cools it contracts. Compressed air wants to expand, as one sees in inflated balloons or fountains. But there is a limit to how much air can be extended or compressed. The air around the Earth has some gravity and presses down, equally in all directions, lightly on a mountain top or in its upper reaches but increasingly so at low altitudes. The atmosphere thus consists of layers, each compressing the one below it and making it heavier. Thus each type of cloud lives in its region, according to its weight. The air presses down on us by as much as 20 Magdeburg yards high of water, but we don't feel it because it presses from all sides. This pressure is not always the same everywhere, and it becomes lighter when rain has fallen. Air can carry moisture, heat and cold, light and sound, and smells. It allows animals to live and respire. When fire and smoke rise, it is the air's weight that lifts them because they are less dense. Just like water, air fills up any space it can by flowing into it.

Chapter II The First Experiment on Vacuum, by Extracting Water

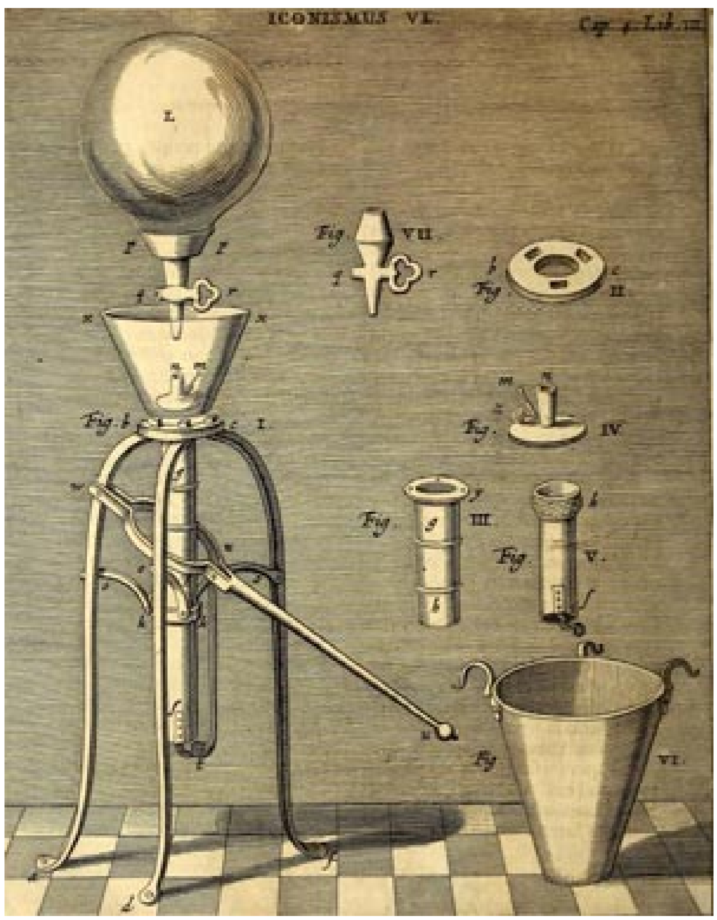
Take a barrel of wine or beer, filled with water and sealed so that no air can penetrate in. Attach, at its bottom, a bronze syringe with a leather valve that can draw water with a piston, of the type that is used to put out fires. Pull out as much water as one can; I needed the help of three strong men to pull the syringe. But a loud sound like boiling water could be heard as the air filled the barrel up. I tried again, this time placing the barrel inside a larger one filled with water. After making sure all the orifices were caulked properly, this time it worked; I'm sure there was left a vacuum inside. However a low hissing sound could be heard, as that of an asthmatic, for three whole days until air filled the vessel again. Where was the air coming from? I had to conclude that water will always pass through wood's pores, generating air in the process, and that there will always remain at most a semi-vacuum.

Chapter III The Second Experiment to get a Vacuum, by Extracting Air

As wood is porous, it seemed to me better to take a copper sphere of about 60 to 70 Magdeburg measures. It had a tap at the top and an opening at the bottom, where I could attach the syringe firmly. Then I tried to extract the air; at first this was easy, but soon enough we needed two men to pull the piston. Suddenly, when we could extract no more air, the vessel collapsed completely with a terrible sound, as if thrown from the highest tower. Perhaps it wasn't perfectly spherical, but it was clear it wasn't strong enough to resist the air's pressure. I ordered a second stronger vessel; this time it did not collapse. When I opened the top valve, the rush of air was so violent that one could barely keep one's hand from being pulled to the orifice. After a couple of days, air again filled the vessel, this time from the valves and tap.

Chapter IV The Construction of a Singular Machine, that produces Vacuum

Since air is so subtle that it penetrates even the tiniest pores, it is almost impossible to prevent it completely from passing round the piston or valve. So I thought of immersing the upper and lower valves of the pump in water, as described by Fr. Schott in his book “Hydraulico-Pneumatica”. Take a tripod, two cubits high and screwed to the ground; a brass cylinder with a lead phlange at its upper end, fits into a brass opening that contains a leather valve that lets air out only. Inside the cylinder is a wooden piston attached to a lever. The brass valve is surrounded by a copper bucket that fills with water. The lower end of the cylinder and piston is also a container full of water so that no air can come in. Place the vessel that is to hold the vacuum on the brass opening, seal it with pitch, and work the handle to remove the air. Raising the piston pushes the air out of one valve and when it is lowered, the vessel’s air empties down.



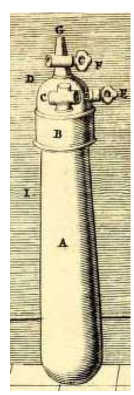
Chapter V The Third Experiment that demonstrates a Vacuum

To make clear demonstrations, I used an upside down glass vessel as used by pharmacists. Its neck is fitted into a brass tube connected to a tap. One can place anything in this vessel: birds, fish, mice, clocks, bells, candles, etc. In my first trial, I removed all the air from the vessel, then placed it into a bucket of water and opened the valve; the water erupted with foam and bubbles into the glass vessel, filling it up to the top, but leaving a hazel-nut sized pocket of air at the top. Even when I immersed the tap in water to prevent any air from coming in, there was still a pea-sized bubble left at the top.

Chapter VI The Fourth Experiment on Vacuum, the Extraction of Water from a Glass Vessel

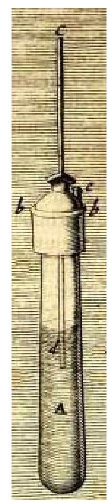
Seeing that there always remained a little air in the vessel, I then tried a smaller "phial" glass vessel with a long neck. I filled it with water and pumped it out, but all of a sudden a large bubble of air erupted out of the valve. After I changed the valve to one made of brass and pitched it thoroughly, I repeated the experiment; still bubbles formed in the water, some from the pitch, but mostly from the water itself. The vacuum was still there because when I placed the flask in water and opened the valve, the water rushed up the vessel as in the previous experiment. Although a bubble of air remained at the top, it was much smaller than the hundreds of bubbles formed in the upward rush. There must be invisible bubbles that grow in the ample space when there is no pressure. This occurs until the water quietens down.

Chapter VII The Fifth Way, making a better Vacuum

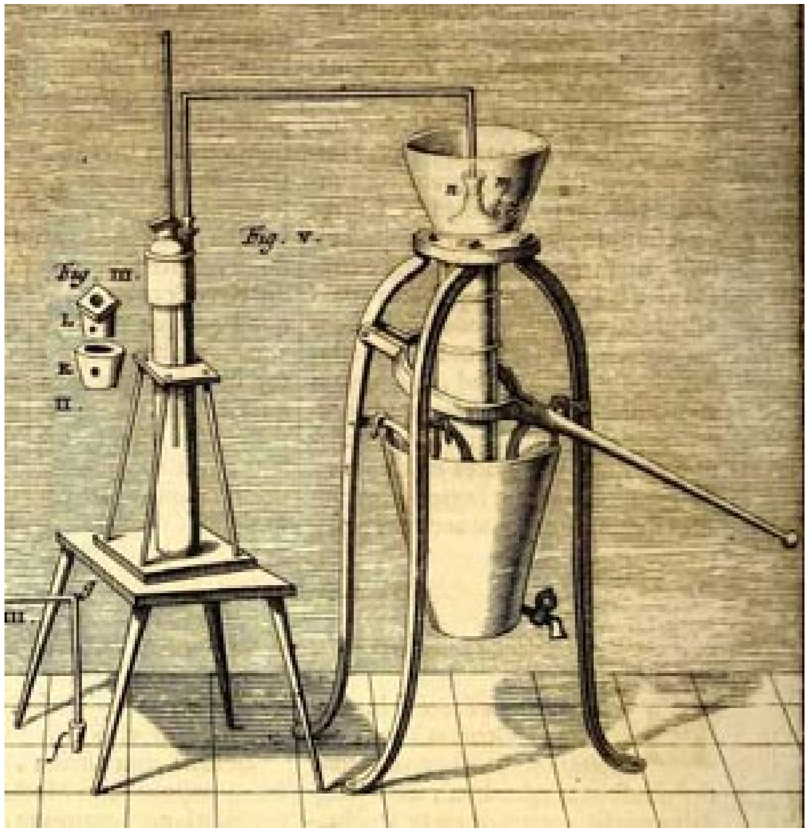


Next I took a cylindrical glass vessel [large test-tube], a Magdeburg cubit long and a man's arm in diameter, with the open end closed by a tap and surrounded by another cover also with a tap. I filled it to the brim with water, and turned it upside down; after a day, a small bubble appeared at the top, which I removed by adding more water. I connected it to the pump after filling it to the brim with water. After making sure there were no more bubbles, I pumped out half the water, and detached the vessel. There were no bubbles formed as in the previous experiments. But upon shaking it, one could hear the water hitting the sides like hard stones, and the flask suddenly shattered, I don't know why. So I had a thicker vessel made and repeated the experiment. Upon shaking, a small bubble formed that grew and the water opened up and closed back internally, with a clashing sound, unlike anything seen normally. These weren't bubbles of air but just empty space, by the way water moves and crashes in it.

Chapter VIII The Sixth Experiment, creating the Vacuum



Sceptics who do not believe a vacuum is possible, such as Dr Deusing, point out that bubbles form and the glass shatters to oppose its formation. They would only believe if they saw the water fall down with absolutely no bubbles forming. So I thought of another device made of an identical [test-]tube. I inserted a narrow vertical tube, sealed at the upper end and filled somewhat with water, down the vessel so that it is always covered in water, and connected it to the pump via another narrow glass tube, well sealed at the openings with precisely machined valves and goldsmith's solder. When the air at the top of the larger vessel was pumped out, the water level in the central tube fell down to that of the other. It fell due to gravity; if it was due to "horror vacui", why would it prefer one vacuum to another? Now tilt the tubes so that the central tube fills completely with water. When it is turned upright again, water flows down the tube without any bubbles forming. Since the lower end of the vertical tube is always immersed in water, no air can enter, so the space left at the top must be a true vacuum. One should note that for the first few days, bubbles keep forming in abundance, even in the vertical tube. One might think that air is seeping in through the glass. But if one leaves the apparatus for eight days, bubbles do not form. Nevertheless, when the central tube is filled with water again, by inclining it, a pea-sized bubble reappears. When the valve is opened to let air in the outer tube, the water compresses the bubble until it almost disappears.



This happens even if the outer air is repeatedly pumped out. So it must be that water continually emits a subtle fragrance of air. Thus it happens that the Earth's seas emit this air into the surrounding vacuum until the air's weight stops it. Also, it follows that there is a limit to the vacuum that can be reached. Some other notes: 1. If water is replaced by beer, then foam fills the whole vessel. 2. If the valve is opened suddenly, the inrush of air pushes the water up the vertical tube with such force that it lifts up the whole machine. 3. Inclining the tubes should be done slowly, else the force of the water is such that it can shatter the apparatus and injure one's eyes. 4. One must also be careful not to shake the tubes too much lest they break. 5. In thin tubes, it sometimes happens that the water does not descend until sharply tapped.

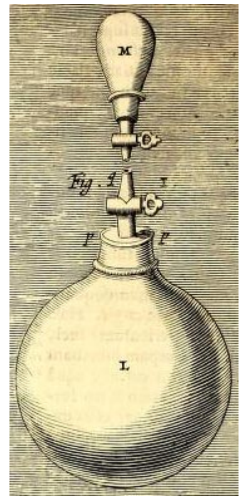
Chapter IX Is a Vacuum natural, or not?

We have seen that whenever we try to make a total vacuum, there always remains some odour emitted by matter, be it water or metal or stone. But if it is impossible to procure a mathematical vacuum down here on Earth, it does not mean that it is theoretically impossible for it to exist. We show this as follows: 1. The atmosphere is a fluid odour on Earth. 2. The atmosphere stays there of its own accord, by its weight. 3. It presses down, the more the lower down. 4. Air pressure changes. 5. It depends on the altitude. 6. By its gravity, air fills out all spaces. 7. This is not because of “Fugam Vacui” but because of air’s weight. 8. The removal of air in a glass vessel results in a vacuum, except that a tiny amount of air is emitted by water. From this follow the conclusions: 1. Earth, like any other matter, exudes an odour. It becomes thinner with altitude until at some point it reduces to nothing. Thus interstellar space has no matter. It is not credible that the tiny amount of air present in our vacuum is enough to prevent the sides from collapsing, as objectors like Descartes need to believe. 2. When air or water is removed from a vessel by a pump, there remains not more than one part in a hundred or thousand of it. But we know why this is: it is the water’s odour. Out in space, where there is none, there would be a true vacuum. 3. Since the air’s weight is measurably less up mountains, we deduce that it does not go all the way to the moon. It does not make sense that a feeble amount of elemental air or fire is what keeps the space between planets in place. 4. Those who deny the existence of vacuum, yet posit that a tiny bubble can fill a whole room, then must agree that it can fill out space, leaving practically nothing but a vacuum. 5. There are others that say that once the air is removed, a rarer aether is able to enter through the glass. But why doesn’t it enter from the beginning then? And if it penetrates glass, why not water? The force emanating from the Sun and planets is dispersed in the empty space, but it is not a substance, and it moves with the body.

Chapter X Experiments on Smells and Fermentation

All objects emit an odour of air, which can often be smelled and is visible as bubbles when the object is immersed in water. Air and odours do not penetrate glass or metal. This air can be trapped in ice and explains why it floats. Fermenting substances, especially when moist or in marshes, emit a lot of bubbles; hence drowned corpses float after a few days. To test this, I placed a dead carp in a small bowl full of water, which was placed upside down inside another vessel of water. After a few days, bubbles of air formed and gathered in the interior bowl.

Chapter XI Experiments to create Clouds, Winds, and Rainbow Colors

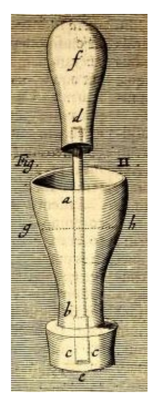


Thermoscopes show that air expands when heated and contracts when cooled. Take a large and a small glass flask, both connected to taps. Pump the air out of the larger one and join it to the smaller one. When the taps are opened, air rushes violently from the small flask. Since rarified air can hold less moisture, the upper flask gets filled with water droplets. Mist and clouds may also form, especially when the flasks are separated and the smaller one's tap opened slightly, until enough air enters to absorb this moisture. Otherwise, the mist sinks and clarifies. Similarly, clouds form as mists rise and interact with the upper air; animals' warm breath is misty in winter as it cools, contracts, and condenses; barrels from cool cellars form sweat as the air cools on contact with it. Finally, the mist in the glass vessels, taken out in the sun, form the colors of the rainbow.

Chapter XII Fire in Vacuum

I lit a candle and placed it in the flask; on pumping out the air, the flame diminished, became violet, and went out. The wick remained glowing for 2 minutes and then expired. Fire cannot live without air. The long shape of a normal flame is due to the air pushing it up, just as water pushes bubbles upwards. With less air, the flame becomes round, like the Sun. If the air is not removed, the flame goes out after 3 or 4 minutes without being blue and round. Thus a flame consumes part of the air, and goes out when it is used up. Legends of torches found alight in some sealed Roman underground chamber are not credible.

Chapter XIII Experiment on the Consumption of Air by Fire



Take an open bottomless flask, pass a narrow tube through it, and attach the narrower end to the tap. Fill the open flask halfway with water and attach to a second flask, in which a lighted candle is placed. As the flame burned, water rose up as a tenth of the air in the smaller flask was consumed before the candle was extinguished. After one minute it descended again, perhaps because of the heaviness of the smoke from the wax. When the air was pumped out, a black smoke formed on the glass; probably the fire converts the air to an earthen substance.

Chapter XIV Light in Vacuum

Some say that there cannot be a vacuum in the flask because objects are still visible – at the very least there is light. But in fact, that would imply that space is some dense substance that can prevent light from passing. Objects are visible because there is light everywhere, uninhibited by glass or vacuum. But in space, light would pass freely, and we would see darkness when we look away from the Sun (as we do in fact at night) or if we look through an evacuated flask.

Chapter XV Sound in Vacuum

I suspended a clock which I fiddled with to strike a note at regular intervals. As I extracted the air, less sound was heard until I had to bring my ear close to the vessel to hear the low muffled sound of the hammer strike. On the other hand, when air was let back in, the sound of the bell was heard again. Then I arranged for a small wooden container to hold the clock, touching it. This time the strikes could be heard audibly with or without air. Hence, it follows that bells and musical instruments tremble the air and this emits sound. But rubbing or hitting objects also creates sound. Thunder and gunshot have the same cause: a sudden fire expands the air, leaving almost a vacuum, which is filled back by air with a bang. Note that if a clock were to be placed in a sealed glass vessel with air, and this placed in the vacuum flask, then the sound would be audible.

Chapter XVI Experiments of Animals in Vacuum

I placed a sparrow in the vacuum flask and evacuated the air. Firstly, the bird could not fly, then it could not breathe though its mouth was open; it remained motionless and died. Then I put in some water with various types of fish. As the air was extracted, the pike swelled enormously and vomited small fish, until they died. Other fish released bubbles of air. When the air tap was opened, the smaller fish revived. Grapes placed in the vacuum flask do not change aspect but lose their taste, the reason being that air pressure forces the flavour to remain inside the grapes.

Chapter XVII A Hydraulic-Pneumatic Machine for a Museum

Connect two flasks together via a tap d, as shown in the illustration. The lower vessel should also have four taps: two of these, f, g, can be connected via a long pipe to buckets filled with water and to two thin pipes inside the flask, one of which reaches to its bottom; the two other taps, connect the outside air to two thin pipes with needle-sharp openings, also reaching to the bottom of the flask. Additionally, there is a finger-wide tube from the bottom of the lower flask to the upper flask via the mid-tap d.

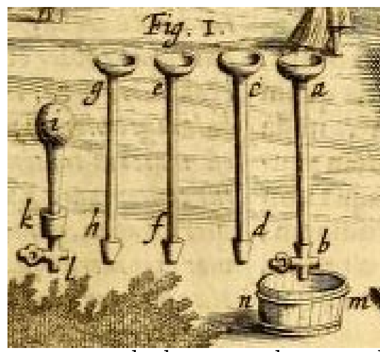
Chapter XVIII The Operation of the Preceding Machine

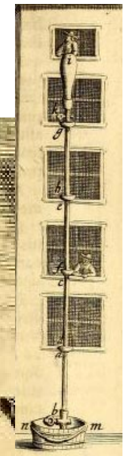
1. Fill the lower flask with water to cover the lower tubes. Use an evacuated copper sphere to remove air from the two vessels through tap f, keeping tap d open. Close taps d and f, and slightly open the other taps. As the air enters the water, it makes a hissing sound that is sustained permanently, even for two or three weeks. 2. Attach to tap f the long pipe reaching to the bucket filled with water. When tap f is opened, water ascends up the pipe into the vessel, against its nature. When the flask is half full, close tap f. 3. Open tap g; air rushes in with an unbelievable violence, until the flask is filled with air. 4. Open tap f and then tap d, but only slightly, so that water ascends up the pipe, hitting the glass of the upper flask with impetus. 5. If tap d is opened hardly at all, the water is forced to break up into minute drops which are seen as mist on the water surface. This is not normally seen on Earth, since the air pressure compresses them into the water. 6. While the lower vessel is being evacuated with the copper flask, and tap d opened, air expands from the upper vessel through the water of the bottom flask. If the lower vessel is completely empty of air and tap d opened too quickly, the rush of air is such that it can shatter the lower vessel. 7. That the so called "Fugam Vacui" is nothing but the weight of the air pressing down is shown in the above experiment: when both flasks are being evacuated, water does not ascend the middle pipe. However, when tap f is opened and air is let in, its pressure forces the water up the tube, until there is enough air in the upper flask to counter it. Whenever tap f is closed, the water stops ascending, but neither does it descend, for if it were to do so it would compress the air in the lower flask. 8. To return the machine to its original state without water in the upper vessel, one needs a small tube u in the upper flask that admits air in and allows the water to descend. 9. When all the water is in the lower flask, attach the long tube, still filled with water, to tap g. It acts as a siphon to extract all the water in the bottom flask.

Chapter XIX A new Fact, discovered by this Machine, indicating that Air has Weight

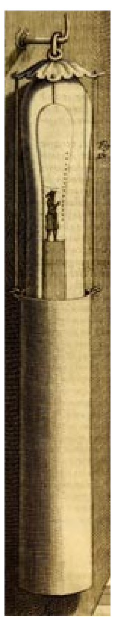
I kept the machine to demonstrate these effects to friends. One of these asked how far up can the water be sucked out of the bucket. To answer this, I extended the long pipe outside the window to the ground below. The water still ascended. So I took the machine to the third floor, with a longer tube, and the water ascended but not as forcefully as before. I had, therefore, to trasfer the machine to the fourth floor. This time no water rose up into the flask. So it was necessary to repeat for a fourth time, with a glass tube glued at a section where it seemed the water had risen to. The height it had reached was 19 Magdeburg cubits, although I noticed that it varied by 2 or 3, from day to day. It could not be that air was seeping in, because it would sometimes rise up. This is further proof that there is no "Fugam Vacui" because why would the water stop where it does, and why would it vary from day to day. Instead, the cause of the variation is external, that is, air pressure in balance with the cylinder of water.

Chapter XX Other Experiments showing Air's Weight and the Extent of its "Fugam Vacui"



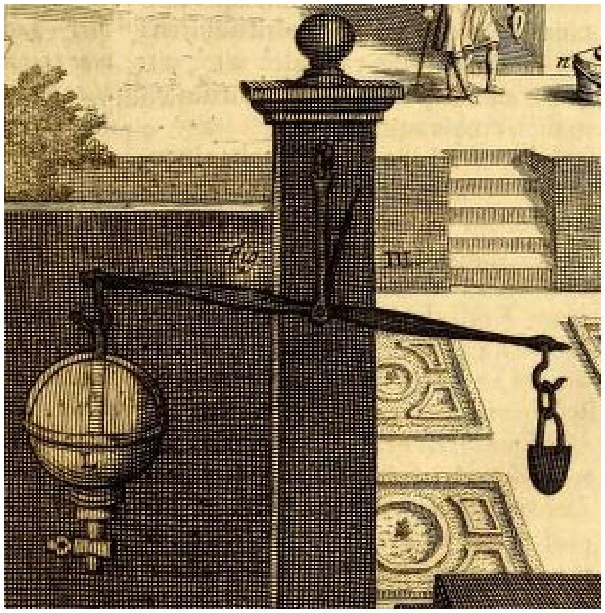


I thought of two experiments that measure air's gravity more easily. First Procedure: Take four brass pipes that fit exactly into each other. One end of each pipe is to be in the form of a cup to be filled with water thus preventing air from entering the joint. Connect three of them vertically to reach a height of about 15 cubits. Attach a tap at the bottom end, insert it into a bucket of water, and fill the pipes with water; also attach a flask filled with water at the top end. When the bottom tap and the flask's tap are opened, the water does not descend because air pressure is enough to counter the water's weight. Now add another length of pipe; this time, the water in the flask falls until the total height is about 19 cubits, which is the total height supported by the air's weight. The pressure does not depend on the tube's width as can be seen by connecting a wide tube with a narrow one via a horizontal pipe. The water level in them reaches the same height.



Second Procedure: Evacuate a flask and attach it to the top pipe. When the upper tap is opened, water rises into the flask, again up to the same height. From these observations, we can conclude that 1. a siphon cannot draw water higher than about 18 cubits. 2. A suction pump cannot raise water from a mine higher than about 18 cubits. In a letter to Fr Schott, I described an invention of mine, called "Semper Vivum", that involves a small wooden statue continually rising and falling inside a glass tube according to the air pressure. The mechanism is hidden to protect and conceal the secret. It balances an evacuated sphere against some weight. Then as the pressure changes, the globe appears lighter or heavier. For example, once when the little man descended beyond the lowest mark, I predicted that a great storm was nearby; in fact, within two hours, a gale came to our region.

Chapter XXI The Weight of Air



The gravity of a cylinder of air of some arbitrary cross section is the same as the gravity of water with the same cross section and 19 Magdeburg cubits high. To confirm this, weigh a vessel full of air, then evacuate its air and weigh it again. You'll find that it weighs about two ounces less; upon opening the tap slightly, the weight returns to its original value. This weight depends on how dense the air is. At a high altitude, air is compressed less because it has less weight on it. Note that even an open vessel shows variations in weight, depending on the air's warmth. Thus the attempts of the most learned to find the relative weight of air and water are futile since it depends on the altitude.

Chapter XXII The Gravity of Cylinders of Air

The gravity of air can be determined by calculation. Measure a container, e.g. 19 centi-cubits in diameter and 38 in height. The area of the base is found by multiplying 19 by 22, divide by 7, then multiply half this circumference by the radius to get 285 square centi-cubits; multiply by the height of 38 centi-cubits to get 10 830 cubic parts. Fill the container with water and weigh it, e.g. $4\frac{1}{4}$ lb. So a container of height about 20 cubits weighs $217\frac{4}{38}$ lb by proportion. This is the weight of air above an area of 285 quadratic centi-cubits.

Chapter XXIII An Experiment showing how Air's Gravity keeps 16 Horses from pulling apart 2 Hemispheres

I took two copper hemispheres of diameter 2/3 of a cubit, fitting exactly with each other. One of them had a valve that prevents air from entering. An annular leather belt, smeared with wax and turpentine, was placed between them for an air-tight connection. When the air was evacuated from them, sixteen horses could not pull them apart. If sometimes they did, an explosive noise would be heard. But when air is let in from the valve, any hand could separate them. To determine the weight that was holding the hemispheres, since the base diameter is 67 centi-cubits, then one finds that the weight of the air is 2686 lb (though it varies), more than what eight horses can pull. To find the weight of all the air one must multiply in proportion the area of the Earth's surface.

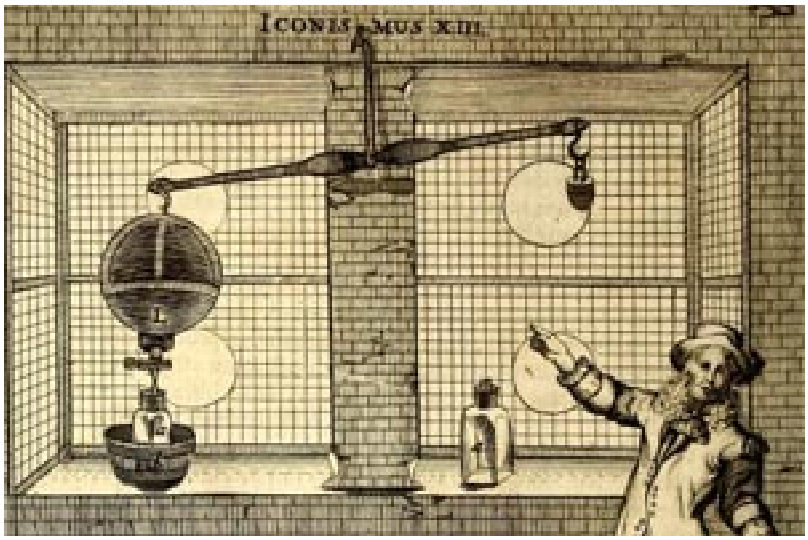
Chapter XXIX A similar Experiment involving 24 Horses

Since the hemispheres were sometimes damaged when they were pulled apart and hit the ground, I determined to make two bigger hemispheres of diameter almost a cubit. By the same calculation as before, the weight of the air on them is 5399lb, more than twice the previous case. Hence 24 horses would certainly not be able to pull them apart, though anyone could do so by letting in air. Since the hemispheres sometimes failed to separate, I also added a tap and a syringe that forces air into them, causing them to separate easily.

Chapter XXV Another Experiment to separate Hemispheres by Weights

I thought of an experiment in which a falling hundred-weight would separate the evacuated hemispheres with a noise as loud as a cannon. Alas, it was not enough to separate them, but I did not repeat the experiment because of the danger to spectators. Instead, to make use of the hemispheres when horses are not available, I had them attached by a hook to a wooden post. To the lower hemisphere was attached a square platform as used by merchants for weighing. Thus one expects that a weight of 2686lb would pull the hemispheres apart; in fact, they did but the sound was more subdued because there is a gradual increase of weight until air starts to enter the sphere.

Chapter XXVI An Experiment showing how Air's Weight can break any Container

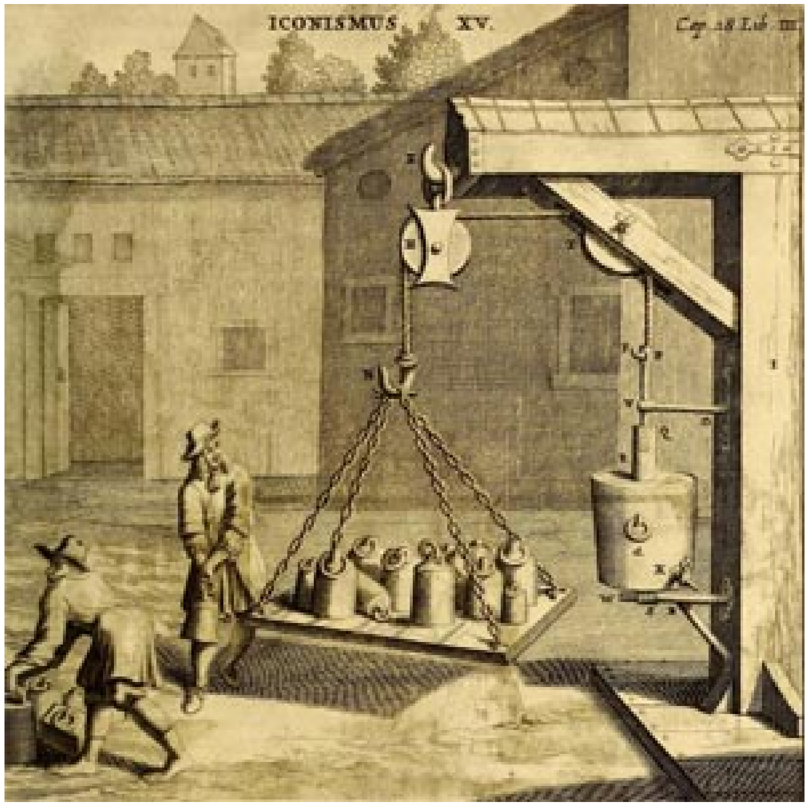


On Earth, air penetrates small spaces in any body, except those completely solid. Conversely, a container evacuated of air would be crushed by the outside air pressure, unless its shape is spherical. Take a spherical glass flask, empty it of air, then attach a square glass vessel to it. When the tap joining them is opened slightly, air flows into the upper flask until the lower vessel is crushed into a thousand pieces accompanied by a loud noise as air enters the flask. If a man were to blow into the evacuated flask, he would die as the air is sucked out of him.

Chapter XXVII A Glass Vessel Capable of Pulling 50 Men

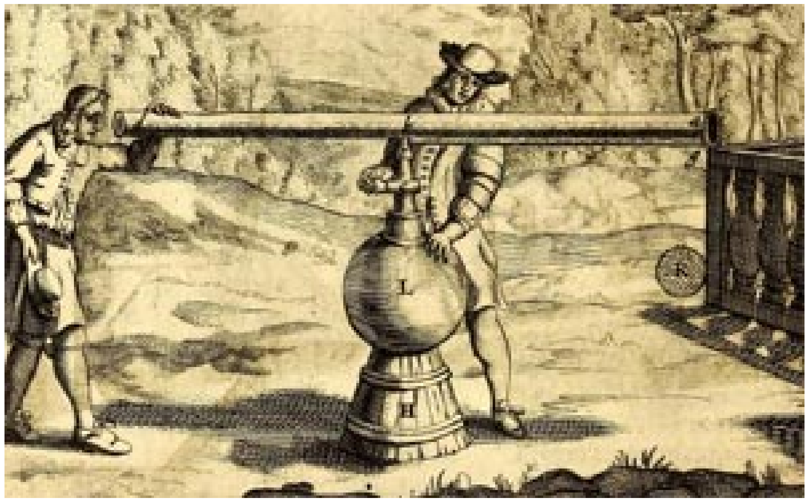
In 1654, when I was on council business in Ratisbon [Regensburg], I showed the Caesar Ferdinand the Third some of my experiments. Some prince doubted my words, so I set up another experiment. I had a copper cylinder made in which fitted a wooden piston made airtight by a flaxen rope, as used for bellows. A tap was attached to the cylinder, and the latter was fixed to a wooden post. A rope passed from the piston through a pulley to a team of twenty men. The piston was first let down to the bottom of the cylinder and the tap closed. Though the men pulled hard, they hardly managed to pull it half way up. Then an evacuated sphere was connected to the tap. When this was opened, the piston was pulled back down despite the men's exertions. If it were to pull against a single man it would rupture his organs.

Chapter XXVIII Elevating a Great Weight



A twelve year old can lift a heavy weight with the preceding machine. The same layout can be used with the piston connected via pulleys to a weight of 2686lb. Attach a small syringe-pump to the cylinder so that even a boy can pull it, the piston is gently forced down lifting the weights up. To lift a larger weight, a piston with a proportionally larger diameter is to be used. The exact weight that can be lifted depends on the air pressure which can be read from the little man.

Chapter XXIX A New Experiment about a Novel Gun



What is achieved in an ordinary gun with much air, can also be achieved with its absence. Take a copper tube of $4\frac{1}{2}$ cubits length with a valve brazed in at one end with a leather disc. Also a thin slit should be cut at this end, connected by a thin pipe to the middle of the tube, and there fitted to an evacuated flask. A lead ball just fitting the tube, is placed at the other end. The tap of the flask is opened and closed quickly. A vacuum is created in the tube causing the ball to be repelled explosively. This can be repeated until the flask is filled with air.

Chapter XXX Experiments that show the Variation of Air's Gravity with Altitude

Air is denser in the lower regions. On top of mountains, the "vacui fuga" is weaker. Take an open glass flask at the bottom of a tower. Close the tap and bring it to the top of the tower; when the tap is opened, air is exhaled. Close the tap again and bring it down to the ground; this time the air is inhaled. It is important that the air is equally warm in both places. Dom de Pachal [Pascal] noted that mercury in a glass tube falls 24 thumbs when taken up a mountain 206 paces high. I tried this myself but my servant broke the tube while he was carrying it. Surprisingly, Dom. Dr. Deusing contradicts Dom. Pequet, who is of our view: "If the air in a lower region is pressed by the air above it, then us mortals in the lowest regions would be flattened by all the air above us." What he should keep in mind is that the air does not press just on our heads but all around us. We do not feel it just as fish do not feel the water's pressure.

Chapter XXXI Experiments that show the Variation of Air's Gravity with Weather

Using the experiments of Chapter 19 and 21, I discovered that air does not always have the same weight. I took a copper sphere with a valve attached to it. I evacuated the air from this sphere and balanced it against an equal weight. Over the days, the sphere and weight went up and down against a scale. When it rains, the air becomes lighter, so the sphere sinks more. A problem is that it is very difficult to produce a sphere in which air does not enter, ultimately rendering the experiment a failure.

Chapter XXXII The Cause of Suction

As air presses down, it fills all pores it is able to, including any partially filled vessel, just as a baby suckles by creating a vacuum with its tongue, or as cupping glasses suck up the skin. Pumps that draw water from wells work by suction. As the piston is raised, it creates a vacuum and causes water to rise. In all cases, the true cause is the air pressing down on the water.

Chapter XXXIII Experiments on the Dilation and Compression of Air

That air has the ability to expand or compress can be seen in thermometers and fountains. The atmosphere weighs on itself to compress the lower layers, balanced by air's power to expand. I had first-hand experience of this when I was working with the machine described in Chapter 18 but forgot to evacuate the upper flask. The air violently erupted into the lower flask. For those who still do not believe in this power, place a full air bladder inside a sphere. When the air is evacuated, the bladder bursts. Or, if the bladder is only half full of air, it swells up. Also, if a pump is placed at the top of a building and connected to a sphere at the bottom, it still evacuates it. What is the cause of air pressure? Some say it is its own gravity striving towards the center. But the tendency to fall should be attributed to the attractive power of Earth. It cannot be due to light from the stars, as some maintain, because the lower regions would be as compressed as the topmost. From this, one can also conclude that the height of air is insignificant compared to the distance to the stars.

Chapter XXXIV An Experiment demonstrating a Vacuum, using Quicksilver

While on council business in Ratisbon, I met the Capuchin Fr Valeriano, who showed me an experiment first performed by Johanne Torricello: Take a glass tube more than a cubit and a half in length, sealed at one end. Fill it with mercury, close the open end with a finger, turn it upside down and immerse in a bowl of mercury. Remove the finger and the mercury falls down to a height of one and a quarter cubits. He claimed that a vacuum forms at the top since nothing could have entered the space. I do not doubt this claim, except that the space is not completely empty. Tiny bubbles remain when the tube is tilted. To study this space, I connected the tube to the evacuating machine after filling it up to a third with mercury. The bubbles rose up with the mercury, but its level dropped by a straw width; pouring in more mercury and repeating the evacuation twice, the mercury fell by half a finger. This is due to the air trapped between the mercury and the sides of the tube. But the machine described in Chapter 4 creates a more perfect vacuum. Fr Schott describes a similar experiment using water, in which a bell was placed in the upper space; a sound was clearly heard, which can only mean that it is not truly a vacuum.

Chapter XXXV Common Objections against the Vacuum

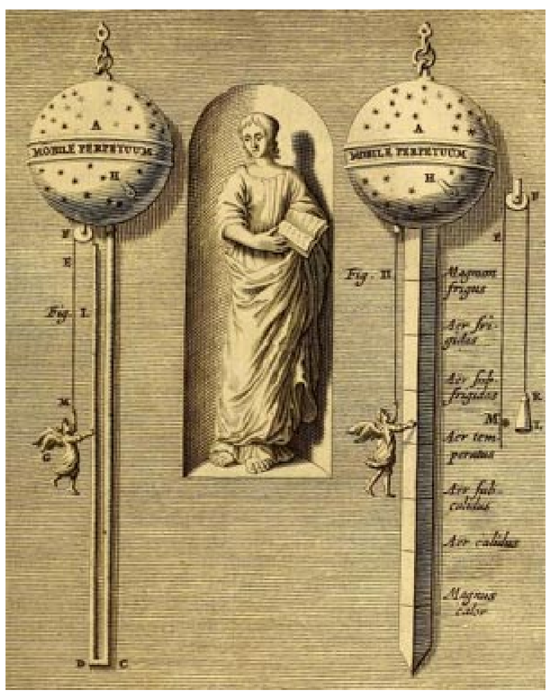
Fr Schott lists a number of experiments that philosophers use to show a vacuum does not exist. 1. Nothing can pull the arms of a bellows apart, if its inlet is blocked. Response: They can be separated with a bar. A clearer demonstration is to take a closed syringe under water and pull its piston. 2. Fr Zuchius wrote about a strong young man who could not pull a flat metal plate with a handle from a marble table. Response: One can calculate the strength needed to pull it up from its area. 3. Immerse a glass in water, then lift it upside down. The glass remains full of water. Response. It can only do this for twenty cubits height, then a vacuum forms. 4. Despite a watering can having little holes in its bottom, its water does not flow out if its upper opening is blocked by a finger. Response: It is air pressure which holds it in. 5. When one sucks air out of a straw in water, it immediately fills with water. Response: If it is "fuga vacui" that is the cause, then water would rise any height. 6. Heat a hollow copper sphere then immerse in water; water is sucked in as it cools. Response: Already answered. 7. It is hard to remove a tight-fitting piston from a gun barrel. Response: Again, it is air pressure that pushes it in.

Chapter XXXVI The Judgement of the Magdeburg Experiments by Fr Kircher, Fr Zuchius, and Prof Cornaeus

In 1654 I demonstrated my experiments to some friends in Ratisbon. I repeated these in the Lord Elector's palace in Würzburg witnessed by Fr Schott and Fr Cornaeus, who relayed them to the learned Jesuits Fr Kircher and Fr Zuchius in Rome. 1. Their first reaction is that the piston cannot be worked indefinitely and at some point the piston cannot be pulled any more. Response: It can be pulled in fact; how hard it becomes depends on the width of the piston. 2. What causes the difficulty? It cannot be nothingness, so it must be that the little air that remains resists further expansion. Response: The little air that remains cannot have a much bigger effect than nothingness. 3. Fr Cornaeus objected that many bubbles enter the water during evacuation. Response: I have described these in Chapter 6. 4. Fr Schott admits there would be a vacuum if a piston can be pulled. Response: Experiments show it can. 5. He also asks how and where is the vacuum formed? Response: The vacuum forms gradually as air is evacuated and expands. Air that expands by heating leaves behind a fifth of the air, while one expanding by extraction leaves barely a hundredth. 6. He relates a case of thick trunks used to lift water from a deep well in Paderborn, which cracked from the suction. Response: They broke for other reasons. I will not reply to the absurd writing of Dr Hauptmann who said that nothing can bring about a vacuum for if the bond of nature breaks, then the sky itself would snap.

Chapter XXXVII A New Magdeburg Thermometer

The common thermometers show the change in air temperature. I devised another way which shows the coldest and hottest days in a year. Take a large copper sphere to which is connected a copper pipe, seven cubits high, joined to another open pipe; pour spirit of wine in the pipe. A tight-fitting hollow tube KL is lowered in to float on the liquid. A waxen thread connects it via a pulley to an angel that points to a scale. Its position is adjusted by extracting air from the sphere. Another method is to balance an open flask against a weight; then as air is denser when it is cold, the flask will rise or fall.



Book 4
On the Virtues of the World

Chapter I Virtues

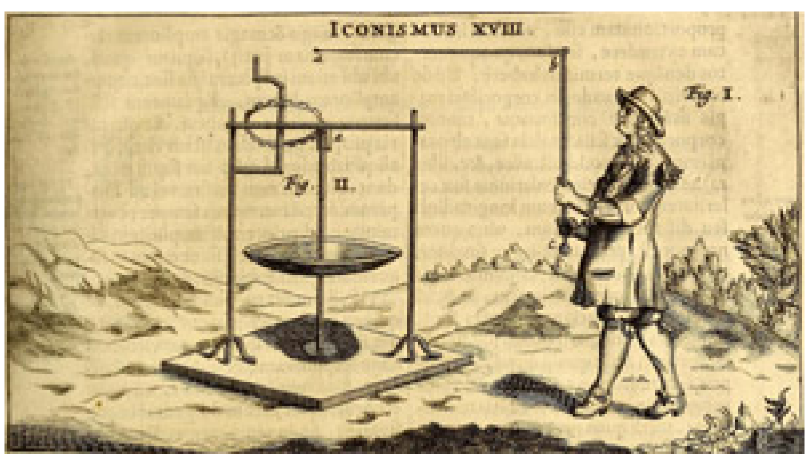
Every created thing, particularly the celestial bodies, planets, Earth, the Sun, etc., consists of its own matter, life, and virtues [$\approx$ forces]. These virtues are inherent in and flow from the celestial bodies, unless they flow into it from another. A corporeal virtue is a subtle extension that flows from a celestial body up to the limit of its orbit, into the surrounding space; it does not pass through solid bodies such as glass, metals, etc., and is distinguished by smell. An incorporeal virtue is one that flows very subtly from the body and extends or diffuses out to a short distance, penetrating solid bodies up to its "sphere of activity". Both virtues are densest and compressed near the body and become rare at greater distances. The virtues that originate from the earth are: 1. Impulsive; 2. Conserving and Expelling [attractive/repelling]; 3. Directive; 4. Turning; 5. Sound; 6. Heat, etc. The virtues that originate from the Sun are: Light and Colour; those of the Moon are believed to be the Freezing virtue. Planetary virtues are called 'influences' by astrologers, but we have scant knowledge of them. The nature of these virtues is to act at a distance, interacting with the same virtues in other bodies, especially the massive solid ones, but reflecting off incorporeal bodies unable to receive them. These virtues can also be aroused by the touch of another body by friction, collision, touch, vibration, etc.

Chapter II The Impulsive Virtue

The impulsive virtue is an Earthly incorporeal virtue that can be aroused in solid bodies when they are violently thrown or spun. By it, the object is carried through empty space or air; the more it has of it, the longer the motion will last. The impulsive force gradually expires when the cause disappears. For example, the impulsive force of a stone thrown upwards disappears, after which a Conservative virtue gives it a downward impulse. When a power falls on a similar hard body, it reflects in the opposite direction, as we see in marble balls on a marble table. Every solid is limited in its capacity of the Impulsive virtue, according to its size and solidity. Those who wrote that objects are capable of indefinitely greater velocity were wrong, even though it has been proven by experiments that heavy things increase their velocity as with the odd numbers 1, 3, 5, 7, 9. As Kircher writes, from Mersenne and Scheiner, that a stone would fall from the firmament to the Earth in 6 hours. But it is true that the larger and heavier the body, the more capable of velocity it is: a lead ball of two ounces hits the ground sooner than a ball of one ounce. Thus a bow, a sling, and a cannon shoots a larger projectile further away. Stones thrown in water do not accelerate, nor do light things ascend as much, due to the water's resistance. A stone thrown upwards in a moving ship, has a double impulse, vertical and horizontal; thus it can return to the hand. A small thing can impart little impulsive force to a large thing; for example, a hammer does not mark an anvil, but it breaks a horseshoe on an anvil on top of a person's belly.

Chapter III The Nature and Qualities of Impulsive Virtue

With one impulse, one can set a straight or circular course, as those in Holland experience on ice. Daily experience shows that a smaller ball, no matter how much force is applied to it, can never be thrown as far as a larger ball. Experiment: A small stone attached to a long string can never be made to rotate properly. Experiment: Make a large wooden concave sphere with an iron rod through the middle; spin it rapidly and place some marble balls of different sizes in it. You will see that the larger ones approach the edge, while the smaller ones remain more to the center.



This may be the reason why larger grains tend to rise to the top, and perhaps why the larger satellites of Jupiter have the larger orbit. The impulsive virtue imparted is proportionate to the object, so that eventually they reach their appropriate distance. For example, in the Copernican system, the planets are carried by an impulsive virtue, or centripetal force, by the Sun and reach a distance proportionate to their size. The larger planets have a wider circumference, but move more slowly. In the Earthly sphere, objects would seek the wider location, namely the Equator. Several scientists, including Galileo, Baliani, Wendelin, and Riccioli, have studied the properties of pendulum oscillations and have found that the height of the pendulum and its mass or weight can affect the period of oscillation. It is mentioned that, by the golden rule, it may be possible to calculate the distance of a planet from the sun from its periodic motion, based on the proportion of the period of the Earth to its distance from the Sun.

Chapter IV Experiment of a Globe in Water

In "Magia universalis naturae", Rev. Dr. Schottus relates that Fr. Kircher in Rome pursued the following experiment, "Fill a glass sphere half with water, and the rest with another immiscible transparent liquid, such as spirit of wine, oil of turpentine, etc. To these add a magnetic ball, which will descend to the middle of the globe and remain there in the midst of the water, just as the Earth stands immovable in the middle of the celestial orb." The ball is kept stable in the middle by a magnet placed beneath the globe. The following is my invention: First, make water that never spoils: expose rainwater to the sun throughout a summer, so that it spoils several times with many worms; then, in the winter, preserved it in a cellar protected from frost; expose to the sun again the second summer, and finally pour through paper into a glass vessel. Second, attach a sheet and an iron tip on the bottom of this glass vessel, so it can be rotated slowly. Thirdly, place a glass sphere, half the size of an egg, of equal weight as water (which can be done by pouring hot water into it then sealed with wax, and lead pieces added to balance it). Depending on the temperature, the sphere will ascend or descend. If the vessel is rotated, the sphere moves out to a middle circumference, which is like the equator. In the same way, the planets, freely hanging in pure space without gravity, are carried around in a circle through the movement of the Sun, and they reach their equator through their impelled virtue. But just as a pendulum vibrates, overshooting first on one side then the other, so also the planets have their excesses on either side. There they cannot stay but are forced to return to their proper place.

Chapter V Earth's Conservative Virtue

The conservative virtue is the incorporeal power of the Earth through which all earthly things unite in harmony; it is not properly an attraction, but rather a union or self-preservation; when one body is united to another by an effluent power. For all things are naturally endowed with the ability to preserve themselves in their own being, either by fleeing the opposite or by uniting. Thus planets preserve their atmospheres from being dissipated or dispersed. In the aerial sphere of power, all bodies seem heavy to us. Nothing in the world is heavy or light in itself; gravity is Earth's conserving virtue that causes difficulty for the person who tries to disjoin, move, or separate it. If the Earth were absent, all bodies would hang freely. The philosopher wrongly wrote that bodies are heavy or light, including the Earth. For example, a strong man who pulls out a stick with his hands cannot be called heavy because he pulls. There is no such thing as a natural desire for a lower place, for when people fall, they do so against their will and nature and often suffer death as a result. This is demonstrated by the sulphur globe described later, which attracts light things even upwards against the the power of the Earth. The Earth itself does not weigh as much as a feather. So Simon Stevin's and Claramons' calculation that the weight of Earth is 2 000 000 000 000 000 000 000 000 pounds is baseless, as are Forerius' figure of 899 000 000 000 000 000 000 000, and Mersenne's figure of 65 900 000 000 000 000 000 000 000 pounds. Furthermore, it cannot be assumed that this virtue exists in the deep interior, as it does in the upper. Therefore, a stone dropped down an endless well would not fall to the center, for the Earth expels what is not suitable to it, as it does with large rocks. Neither is this virtue limitless up to the other planets and stars.

Chapter VI Earth's Repelling Virtues

Aristarchus believed that the Earth has a sensible soul that has the power of attraction and repulsion to what is beneficial or harmful to it. This can also be seen in the sulphurous globe mentioned later, for if it rubbed a few times by hand, it sometimes attracts light things, and sometimes repels them at will, as it wishes. Thus it attracts a feather, then repels it and one can carry it around a room, perhaps to acquire something from it. Similarly, the Influences of the Planets vie with each other, depending on how close they are to each other. The Earth and Moon, however, being always carried close to each other, act on each other the most, in particular the virtue that produces Cold, which in winter, is sometimes received and sometimes repelled by Earth. For this virtue cannot produce a greater effect than when the rays of the Sun are weaker and the Earth is deprived of all heat.

Chapter VII Earth's Directing Virtue

The directing virtue is an incorporeal virtue (it penetrates all things, even glass) that is inherent in the magnet, but which extends throughout the entire Earth with the poles as its natural boundaries. For example, if the Earth were somehow to be tilted from its axis, this virtue would return it to its original position. For, just like a lathe, the Earth needs a force to keep its axis fixed. Only in the ferrous magnetic veins does this virtue take root to persist in it. The Earth is not a large magnet, as some believe, but at least it has the rotating virtue. And this is necessary since the earth is subject to oscillation due to the impact of the solar rays; since nature does nothing in vain. Experience shows that this virtue has no use other to turn objects, unlike what some people said, who, carried away because they were unable to produce new experiments, filled the world with false conjectures and fictions and infamous magnetic ointments and other fraudulent remedies. This virtue can be excited in any iron by hard rubbing, as for example, when one takes an iron wire directed north-south and strikes the ends with a hammer. Indeed, window iron frames, acquire this virtue after fifteen years or more. It should also be noted that the magnetic virtue is stronger in the upper parts of the earth than in the inner depths, which can be seen from the fact that the magnetic needle almost always has some deviation, either to the east or the west, and therefore corresponds exactly to the meridian line in only a few places. The reason is that the compass is affected by this virtue by surface magnets. Moreover it has been observed that the magnetic deviation is not constant in the same place. Finally, it should be noted that a magnet has two faces, the southern and the northern, or rather has one simple virtue that keeps the poles' axis in a fixed orientation on Earth, just as the human body has a natural orientation with the head up and the feet down.

Chapter VIII The Difference between the Conserving and Directing Virtues

The union of magnets at their poles is improperly called attraction; for it is not the magnet that draw the other, but the magnetic virtue that enter the magnet and the iron. This is the great difference between the Conservative virtue and the Directive virtue: the former attracts all bodies in all places, and so they move straight to Earth's center; the latter attracts or repels directly only at the poles and obliquely in the other parts. So the Conserving power is the accumulation of Earth, and the Directing power is its arrangement. There is a great difference between magnetic and electric attraction. Gilbert in "On the Magnet" wants to say that electric attraction is the seeking of the humid to the humid, but this is criticised by Caleus in "On the Philosophy of the Magnet", who thinks it is due to the flow of pure thin air which drives air away thus drawing in other particles when it returns. But this cannot be right, because an electric sulphurous globe can exert its attractive virtue through a fine thread, an ell away.

Chapter IX The Turning Virtue

The Turning Virtue is responsible for turning a body about its axis. What use would the Directing Virtue be, unless there is circulation to determine its vertex? A stationary body has no need for direction. We see the turning virtue in the children's spinning tops, the more solid the more its capacity for this virtue. We also see it when it revolves the entire Earth, including the Air and the Moon itself. Thus it has two parts: first, as it pertains to the moving body itself, and second, as it accidentally carries another body in its orbit of virtue, the weaker the farther away the body is; e.g., the Earth rotates in 24 hours, while the Moon takes $29\frac{1}{2}$ days. A body may be able to excite the turning virtue by itself (as in men who jump and spin without any aid). It is helped by the Impulsive virtue, as jugglers do when, with a single impetus, rotate on the ball.

This virtue allows the Sun to carry around the planets, and the planets their satellites. This Virtue, which we do not perceive, turns the Earth at 384 steps per second. This is not surprising: for who among us feels the impulsive virtue in their body, or their weight, or who preceives a moving ship when completely enclosed in it? Or who senses the pressure of the atmosphere?

Chapter X The Sound Virtue

Sound is an incorporeal virtue that is excited by the collision of corporeal things, when they move against each other, like a hammer on a bell. The sound spreads in a sphere, within which it may reach our ears. The sonable virtue varies according to the matter composition, place, and temperature. Although colliding bodies may not make a perceptible sound, there is still a sound: dogs can hear sounds that we do not hear, and we ourselves hear more at night, just as our eyes do not see the smallest things. Even air moving against air produces a whistle or roar. Sound is not carried by air, as philosophers commonly hold, but it penetrates everything, including hard corporeal things that air cannot penetrate (see Book 3, Chapter 15). The sound of a bell can still be heard clearly through a completely sealed glass. Sound can be transmitted in an instant through very long beams; if one person lightly scratches one end, another person can clearly hear it at the other end. But the more porous a body is, the more easily it can be penetrated by sound, hence air can be penetrated much more easily than water, and stone more than metal. If sound is carried by air, then how do we hear better in perfectly calm days when the air is not moving? Sound travels through water but not as well as in air: Divers also hear loud noises in deep seas, and fish gather when they become accustomed to a bell. That sound affects other bodies can be seen from the fact a vibrating string induces another string that is not touched to also produces the same sound. As Mersenne reports in "Harmony", when the organ of the Franciscan temple in Paris is played, the surrounding wall and floor is shaken so much that you almost fear the earth will break apart. Similarly, Fr Kircher writes of a large stone in Rome that trembles at a particular organ sound. And excessive sound can make someone deaf.

The power of sound weakens with distance. It does not spread instantaneously like light; it can be reflected in an echo, like light and the impulsive virtue. Resonance, on the other hand, is the reflection of sound from a body incapable of the sounding virtue; the quality of the sound changes, just as an opaque body reflects light differently from a transparent one. Although reflections of other virtues are usually stronger from flat or smooth bodies, we often hear echoes better in snowed-under forests. In the valleys near Helmstedt, one can count the echoes one after another when a gun is fired. Other places can produce extremely clear echoes of voices and music, as Lucretius writes in "On the Nature of Things": "The hills, repeating the words, repelled the words." Whether there exists a stone able to absorb sound and reemit it, no one knows, just as no one before believed that sunlight could be absorbed by a stone and remain preserved in it for some time [lapis solaris]. Perhaps that is what the ear bones of animals do. Moreover, sound has a remarkable quality of harmony, which both humans and beasts can perceive.

Chapter XI The Heating Virtue

The heating virtue is an incorporeal virtue that can be excited in bodies (except water) through friction. It penetrates into bodies over time. The more the friction is repeated, the more the heating virtue increases, until fire results, as we see in wood, stones, iron, etc. The same must be concluded about underground fire which must be excited through hard friction. Like the other virtues, it is scattered outside the earth. It must be assumed that this fire is secondary, that is, taken from the sun by friction, especially when concentrated as through convex glasses. Heat is ably absorbed by a sulphurous or fatty object, and hindered by the contrary element, namely water; the denser the more capable, while the rarer it is, like air, the less so. Therefore, in vacuum, where there cannot be any friction, there can be no heating, much less fire. The most concentrated heat is the flame, which is preserved by the fat and airy substances around it. The heating virtue extends a body, and can dissolve a substance by breaking it into small parts. Freshly prepared glass drops dropped into cold water, are externally solid but internally porous and rare. The heat dissolves and dilates the glass but the water hardens its surface; when the heat escapes, the interior remains porous, so that when such a drop is broken, air rushes into these pores, reducing it to dust.

Chapter XII The Virtue of Light and Color

From the sun flows the virtue of light. This virtue, when it touches a body, heats and illuminates it. This innate light is the primary light; the reflected light is accidental and called the secondary light, then tertiary, quaternary, etc.; for example, the secondary light from the moon after it is reflected from the sun. This virtue has its own properties: it only touches some objects at the surface (opaque), in others it penetrates (transparent), for example, air, water, glass, the crystalline humor in eyes, etc. Light becomes weaker with distance, so someone standing at the bottom of a sufficiently deep well would see the stars even at noon. Looking away from the sun, out in space without any object for light to impinge on, we would see nothing but darkness. Light spreads out unimpeded in vacuum until it hits a planet. Light can be retained for a certain amount of time in the luminous stone from Bologna; it continues to shine for a time, like a live coal.

Colors are reflections of light according to the quality and position of the body. Some are virtual immaterial colors as in the rainbow and triangular glass. Other colors are material, because matter participates in its reflection. The blue color of the sky arises from black and white, at the place where the air's humidity is rarefied and the black of of the upper pure air begins. This is just as a drop of milk and a drop of ink placed next to each other produce a blue color. Thus, at twilight, the finger leaves a perfectly blue shadow on a white paper.

Chapter XIII The Nature and Qualities of Sight

The crystalline humor in the eyes of animals is a body able to transmit light, and so allows vision, that is, the perception of objects. All vision occurs through the so-called visual angle. The further the distance from an object, the smaller its visual angle. Thus closer objects appear larger, not because they are so, but because they have a larger angle. Thus a star which is 229 times distant as its semi-diameter appears at an angle of $30'$ minutes, which is in fact, the visual angle of the Sun and Moon. The reasoning is this: An equilateral [isosceles] triangle ABC has angle BAC equal to $30'$ minutes; so half the angle is $15'$, and its complementary angle, at B or C, is 89-$45'$ degrees; its tangent is as 10000 to 2291816. So the ratio of the radius BD to the tangent DA are as 1,0000(4 to 229,1816 (196940 German miles). If I want to know at what distance the Earth will appear the size of Venus, which subtends a visual angle of $2'$ minutes, then take half that angle, and seek its tangent, which is 3437 semidiameters. Conversely, one can work the visual angle from the distance.

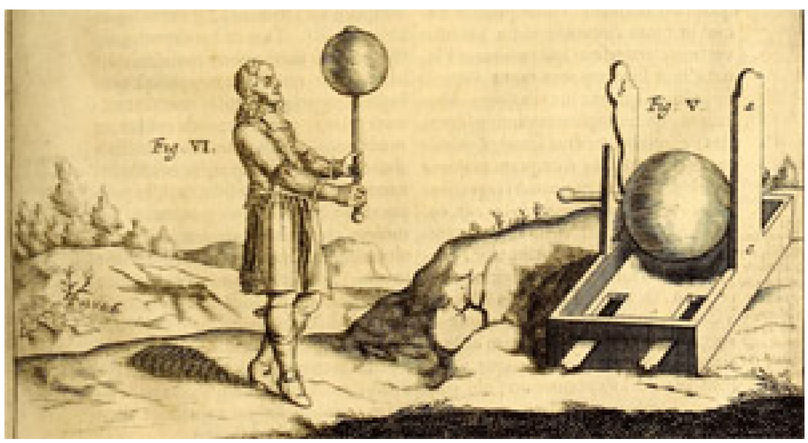
Chapter XIV The Difference in Appearance of Distant Stars

1. The difference between Light and Lumen, is that the former comes from shining bodies, such as the Sun and fixed stars, while luminous bodies reflect light coming from elsewhere, such as Planets and their satellites. It is reasonable to think that planets are smaller than the stars. 2. Both light and lumen get weaker with distance. A little flame is visible at a distance where a large opaque object is not. Therefore, extremely distant luminous body appear larger than one expects from geometry. The reason for this is that the radiant sphere around these bodies is invisible up close, but becomes apparent at a distance, so that stars appear larger than they should be; one sees not just the star but also their radiant sphere. Thus, Mars in opposition to the Sun and closer to Earth, should be five times the size of when it is in conjunction, but appears to be only twice as large in reality. The same thing happens with New Stars, which do not increase in size as much as they should as they get closer to Earth. 3. This effect is even more apparent in planets, being closer, so that they appear the same size as stars. The Sun appears larger than if we were to see it from Mercury because the radiant sphere is more concentrated. Clouds appear by day the same color as the Moon, but in the evening, illuminated by the Sun, they appear fiery. One can conjecture that a comet is air that is condensed high up in the sky, but farther away it appears as a new star. 4. It is shown in book 5 that the atmosphere makes stars appear larger than they are in reality, especially when they are near the horizon. 5. We have found that stars are surrounded by rays so that their bodies appear enlarged; as we see in torches seen from a distance. The cause of these rays is the reflection in the membranes

above the pupil, which is only perceived at a distance. Longer rays also appear due to the eyelids when they are held narrower. In fact, bright stars appear larger to the naked eye than in the telescope which removes these adventitious rays. Therefore, Galileo in the "Cosmic System" thinks that the diameter of stars is 5 seconds rather than 2 minutes as they actually appear. 6. This also happens with Venus, which during its conjunction with the Sun should appear much larger than in opposition, but in fact is not even double in size. The reason for this is that it is crescent shaped and reflects much less light. 7. Changes in the size of the fixed stars is not to be compared with that of the Planets becoming larger or smaller. They are at too inmmense a distance relative to the planets for their apparent size to change appreciably. 8. Regarding Jupiter, its diameter appears larger than the other planets because it is surrounded by a larger atmosphere. 9. Stars at extreme distances reach the limit of what can be seen, not because of their size but because of the weakness of their light.

Chapter XV An Experiment that excites the Virtues in a Sulphurous Globe

Take a glass sphere, called a phial, the size of an infant's head. Crush sulphur in a mortar and pour into the sphere, melting it just enough when placed over a fire. After allowing it to cool, break and remove the phial, preserving it in a dry place. The globe may be pierced with a hole so that it can be rotated with a steel rod as an axle.



1. The Impulsive Virtue can be excited in this globe, especially since it resembles metals in weight. It will continue to turn farther than wood or lighter materials.

2. To demonstrate the Conserving Virtue, rotate the globe on a pivot, rubbing it with a dry palm, and apply various bits and pieces, such as gold and silver foil, paper, hops, etc. It attracts these fragments and carry them with it. In this way, Earth is placed before your eyes, which attracts and carries with it all the things on its surface in its daily 24-hour motion. This globe makes

water droplets swollen, and also attracts air and smoke. This was known to the ancients to have an attracting and expelling power.

3. The Repelling Virtue can also be clearly seen in this globe. Depending on the temperament, it repels small bodies, such as feathers, away from itself, and does not receive them again until they have touched another body. Those feathers, pushed upwards, can be sustained longer in the orbit of this globe's power and can be made to circulate around the entire room as you wish with the globe. It is worth noting: i. A soft feather, both when on the globe and in the air, is lively in a certain way; it is attracted to any nearby object, e.g., it can stick to someone's nose. However, it seeks refuge from a burning candle towards the globe. ii. The same side of the feather, which has once touched the globe, remains facing the sphere. Whether the same reason causes the Moon to always look at the Earth with the same face will be discussed in Book 5, chapter 20. iii. If the feather starts to spread its branches while on the globe, and you place a finger in front of it, it flies towards it, doing this several times. But if you put a string in front of the feather, all its arms will be completely joined to the globe as if dead for a longer time, until they stand up and extend again. In a similar way, the feather is so afraid of fire that if it spreads itself in this way and the flame of a candle is placed close to it, it will throw itself onto the globe. iv. If you lower a string hanging from above almost to the globe and try to touch it with a finger or something else, the string will move away from the finger. v. If you hang a string on a stick fixed on a table, and place the other end to a distance of an elbow above the ground, and bring the excited globe close to the stick, the string can attract light objects within a thumb of it, showing that this virtue has extended itself in the string to its farthest end. vi. If this globe on the rotating machine is excited by the palm, a soft feather placed on it will often be attracted and repelled from any nearby surface location around it for several hours. vii. It often happens that the branches of the feather will spontaneously apply themselves to what is being held out to them, or even suddenly compress and bend, and in this way they will show the antipathy that the globe feels towards the feather at that time. In a similar way, scattered branches, if you try to grab them with your finger, will reject being touched, reflecting themselves and bending themselves towards the globe.

4. The Directing Virtue cannot be aroused in this globe since no other bodies except for the magnet and iron possess it.

5. The Turning Virtue cannot be conveniently demonstrated, for the feather is drawn too much towards the Earth by its Conserving Virtue, and thus the circulation is hindered. However, this power can clearly produce the sensation of dizziness in the feather itself, as well as its turning as mentioned in article 3(ii) above.

6. There is also a Sound Virtue in this globe: when it is carried by a warm hand and brought to the ear, noises or thunders are heard in it.

7. The Heating Virtue can be aroused in this body by continuous and hard friction, so that if the heat becomes very intense, fire is finally ignited.

8. The Luminous Virtue is also produced in this globe in a similar way. If you bring it into a dark room at night, it shines in the same way as sugar when

pounded. Let's pass over in silence other hidden things that are manifested in this globe, for Nature (as Kircher says in the "Art of Magnetism") often exhibits wonderful miracles in even the most worthless things, which remain unknown unless they are investigated by those with a keen and scrutinising mind who use experience as their teacher. Mr De Monconys mentions in his Journal of Travels through Germany that he saw this Globe and its operations among other new experiments of the author in the house of Magdeburg, but he lost his notes.

Chapter XVI Other Corporeal and Incorporeal Virtues

There are diverse unknown virtues, both corporeal and incorporeal, used by animals to live. Corporeal virtues consist of airy effluvia and scents. They are not equally sensed by all animals, but differently according to their nature and qualities; man has one sense of smell, the eagle another, the dog another, the deer another, etc. There are undoubtedly many more incorporeal virtues, but since we lack the organs that can properly feel these virtues, they remain hidden to us. For example, the virtue that is imparted to the skin through friction, which stops itching, is unknown, even though it is frequently used among animals. Then there is the virtue that causes fermentation and corruption in things, such as we see in quicklime and grains. Others cause diseases and disorders, or promote digestion in the stomachs of animals, etc. We know next to nothing about them. Furthermore, no doubt, each planet has its own virtues emanating from them into the surrounding space far and wide; and they affect each other according to the different positions of each, whether closer or more distant, in Opposition or Conjunction, etc. These virtues, called Influences, are either good or bad according to the different times and the affections of these celestial bodies towards each other, and they cause their effects in every body. Primary is the influence of the Moon, which is essential for all the animals, not to mention the Sun. However, these effects are not so specific that astronomers can reasonably predict the weather, fertility, barrenness, rain, wind, diseases, and wars of a particular city, region, or people, and give sure predictions. As Reita wrote in the Eye of Enoch and Elijah, "who has penetrated the secrets of such events as eclipses in terms of their effects on our Earth?" Why then do these deceivers and charlatans, the astrologers, not blush to divine about future events from the stars, when they are ignorant of even their present effects? And since they always write with ambiguity, it is not surprising that by pure chance it sometimes happens in accordance with their predictions, and thus believed by simpler people, as Farnesius wrote in "Natural Philosophy". Mersenne in his notes on Aristarchus, writes: Since the Earth emits vapors spontaneously or through some kind of ejective force, it is useless for poor judges to torture themselves trying to attribute the causes of rain, thunder, wind, and other such effects to the planets and the sky, when they can find what they are seeking much closer to the Earth they inhabit. In fact, we know just as little about celestial objects, such as the lunar libration, the unknown companions of Jupiter and Saturn, the changing of solar spots, etc.

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