Afterword: Galileo's Boat

Prof. Roman Frigg

IN 1632, SHORTLY after the publication of *Dialogues on the Two Chief World Systems*, eminent Italian physicist, mathematician and philosopher Galileo Galilei was summoned to stand examination by the Holy Office of the Inquisition in Rome. In June 1633 he was found 'vehemently suspect of heresy' and forced to abjure.

His heresy consisted in defending the Copernican theory of the universe. The traditional worldview, originating with Aristotle and given a canonical form in Ptolemy's *Almagest*, sees the earth as the immutable centre of the universe. Other heavenly bodies, including the sun, move around the earth, which explains the pattern of day and night on earth and the observed motion of planets in the sky. Copernicus' *On the Revolutions of the Celestial Spheres* proclaimed the bankruptcy of this view and announced a fundamental reshuffle of the cosmic order: the immutable centre of the universe is the sun, and the earth is moving around it. Having attributed to the Ptolemaic view the status of an untouchable dogma, the Church did not look kindly on what it saw as a violation of the injunction against promoting a heliocentric universe. Galileo was forced to repudiate his views:

> 'I have been judged vehemently suspect of heresy, that is, of having held and believed that the Sun is the centre of the universe and immoveable, and that the Earth is not the center of same, and that it does move. Wishing, however, to remove from the minds of your Eminences and all faithful Christians this vehement suspicion reasonably conceived against me, I abjure with a sincere heart and unfeigned faith, I curse and detest the said errors and heresies, and generally all and every error, heresy, and sect contrary to the Holy Catholic Church. And I swear that in the future I will neither say nor assert orally or in writing such things as may bring upon me similar suspicion.' (Quoted in William R Shea and Mariano Artigas: Galieo in Rome. The Rise and Fall of a Troublesome Genius. Oxford University Press: New York, 2003, p. 194)

Legend has it that he acquitted this abjuration with the famous 'eppur si muove' (and yet it moves), declaring that the earth moves around the sun after all, official dogma notwithstanding. The sentence was sufficiently ambiguous to get way with, but the consequences of the condemnation were severe. Galileo had to spend the rest of his life under house arrest, and *Dialogues* was added to the index of prohibited books (where it stayed until 1835; a formal pardon from the Church had to wait until 1992).

The doxastic reasons for rejecting the heliocentric worldview are of historical interest but need not occupy us here. What is of interest, even to the modern reader, are the empirical refutations heliocentrism allegedly faces and how Galileo dealt with them. The argumentative strategy underlying these alleged refutations is to establish that the earth cannot possibly move because if it did there would be all kind of observable effects, which are, however, never observed. Consider a ball dropped straight down from a tower. If the earth was moving at hundreds of kilometres per hour, the ball would not land at the bottom of the tower but far behind it because the tower has moved while the ball was in the air. However, we do observe balls to land at the bottom of the tower when dropped. On a moving earth we also would have to experience constant strong winds, analogous to the draft we feel when driving fast in an open car, and we would see that birds would not be able to fly in all directions with equal ease. Yet we experience no such winds and birds do not fly in privileged directions. On a moving world, a little pile of grains on a plate would slide off the edge just as they would if you suddenly started spinning the plate on some fulcrum or pivot underneath. But no such dispersion is ever observed: grains remain as a little pile on the plate. For these reasons the world must be at rest.

To uncover the flaws in these arguments Galileo invites the reader to imagine the following scenario:

> 'Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a narrow-

mouthed vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction. When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. In jumping, you will pass on the floor the same spaces as before, nor will you make larger jumps toward the stern than toward the prow even though the ship is moving quite rapidly, despite the fact that during the time that you are in the air the floor under you will be going in a direction opposite to your jump.' (Galileo Galilei: *Dialogue Concerning the Two Chief World Systems*. Translated by Stillman Drake. The Modern Library: New York 2001, pp. 216-217)

The reference to butterflies and fish rather than measurement instruments and laboratory equipment is deliberate, to render the point immediately obvious to common sense and to make its relevance to everyday life obvious. The modern equivalent of this thought experiment is the observation that life goes on as usual even if we are in an aeroplane flying from London to New York at over 900 kilometres per hour: if you drop your glass it lands at your feet, not at those of the passengers five rows behind you. And so on. Claire Dean's story takes up the theme of invariance in a different frame of reference: her actors are humans, rather than butterflies or fish, with all of their emotions, desires and thoughts. Yet Galileo's observation stands: behaviour off shore is just like behaviour on shore.

Galileo's point was simple and striking: the moving earth is like the ship! Just as the motion of the ship is not observable for those on board because all process and motions take place as they would on land, the motion of the earth is not observable for us because motion does not change the way in which things move. In fact, everything inside a moving object – be this a ship or the earth – has the same forward motion and when the ball falls from the tower it in fact keeps moving forward at the same speed as the tower itself, which is why it lands at the bottom of the tower and not behind it.

We now know that this argument is only approximately true. Unlike the ship, which is assumed to move on a straight line at constant speed, the earth moves in an elliptical orbit and it rotates around its own axis. This has an effect on the motion of objects on the earth. However, the effects are so small that they are negligible in everyday contexts, and the effects anyway aren't the ones Galileo's critics had envisaged. In the tribunal of history Galileo was the clear winner of that debate.

There is a deeper message in this thought experiment. Setting aside picturesque analogies and cutting to the deep structure of the argument, what Galileo showed is that the laws of nature are the same in a system that is at rest and one that moves at constant speed. This is now known as the principle of 'Galilean Invariance'. The significance of this insight can hardly be overestimated. It introduced into physics the notion of studying invariances and symmetries, which has become crucial in all branches of modern physics, most notably in Einstein's theory of relativity. So the though experiment with the ship not only proved arguments against the heliocentric worldview wrong; it also gave physics one of its most powerful theoretical instruments.

Supported by the Institute of Physics and Arts Council England.