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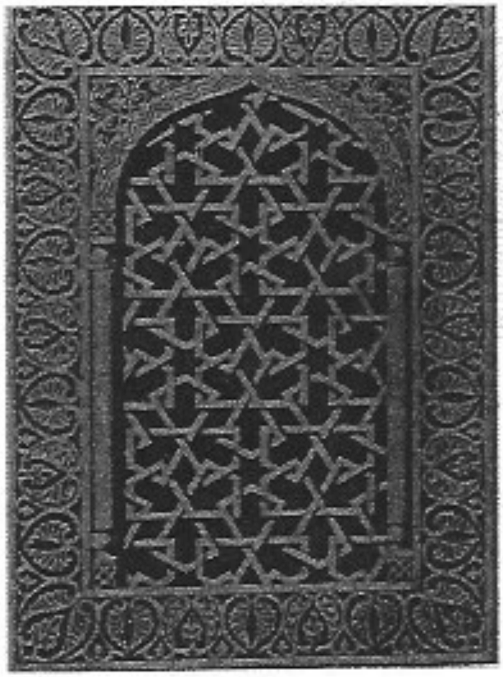

Symétries

Contributions au séminaire
de Han-sur-Lesse,
septembre 2002

éditées par
Patricia Radelet – de Grave
avec la collaboration de
Cathy Brichard

Réminisciences 7

BREPOLS

> You say, then, that since when the ship stands still the rock falls to the foot of the mast, and when the ship is in motion it falls apart from there, then conversely, from the falling of the rock at the foot it is inferred that the ship stands still, and from its falling away it may be deduced that the ship is moving. And since what happens on the ship must likewise happen on the land, from the falling of the rock at the foot of the tower one necessarily infers the immobility of the terrestrial globe[2].

He then simply denies the 'observations' on which this argument is based, claiming that the stone always falls to the same place whether the ship is at rest or in motion, and thereby turning the argument on its head :

> the stone always falls in the same place on the ship, whether the ship is standing still or moving with any speed you please. Therefore, the same cause holding good on the earth as on the ship, nothing can be inferred about the earth's motion or rest from the stone falling always perpendicularly to the foot of the tower[3].

This claim is generalised in his famous ship experiment, later on the same day of the *Dialogue*.

> For a final indication of the nullity of the experiments brought forth, this seems to me the place to show you a way to test them all very easily. 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 wide 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

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[2] 1632, GALILEO, p.144. Cet article cite selon la traduction anglaise de 1967.

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> To observe the transformation is to observe both the unchanged reference and the changed system[8].

In other words, the first step is to observe the transformation, which involves transforming a subsystem with respect to some reference that is itself observable. Applying the transformation to the subsystem must yield an empirically distinct scenario. The second step is to observe that the symmetry holds for the subsystem of the universe :

> observation of a symmetry will always require two components : One must observe that the specified transformation has taken place, and one must observe that the specified invariant property is in fact the same, before and after[9].

The Galilean ship experiment is an example of *directly observing* a symmetry. We observe that a transformation has taken place by observing the two empirically distinct scenarios of the ship at rest with respect to the shore and the ship in motion with respect to the shore. We observe the symmetry be noticing that everything happens inside the cabin of the ship in exactly the same way, regardless of whether the ship is at rest or in motion.

All the familiar global continuous space-time symmetries –spatial translations and rotations, temporal translations, and boosts– have this same *direct empirical significance*. Each of the associated transformations can be applied to Galileo's ship, and the results of the experiments carried out in the cabin remain the same, regardless of the location, orientation, time or state of uniform motion of the ship.

2 Observing other symmetries

The global continuous space-time symmetries are not the only symmetries of modern physics. The concept of symmetry in physics underwent several important developments in the twentieth century. Two of these were :

(1) the move from 'global' continuous symmetries, such as the familiar space-time symmetries we have just mentioned, to 'local' continuous symmetries (of which more below) ; and

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[8] Kosso 2000, p.87.

[9] Kosso 2000, p.86.

exact global internal symmetries have no direct empirical significance[14]. This leads to the question : where does the empirical significance of global internal symmetries lie? We will come back to this question in section 3, below.

The other development in the concept of symmetry mentioned above is that from global symmetries to local symmetries. The terms 'global' and 'local' are used in philosophy of physics with a variety of meanings. The distinction intended here is between symmetries that depend on constant parameters (global symmetries) and symmetries that depend on arbitrary smooth functions of space and time (local symmetries). The gauge symmetry of electromagnetism (an internal symmetry) and the diffeomorphism invariance of General Relativity are examples of local symmetries, since they are parameterized by arbitrary functions of space and time.

It turns out that local symmetries, be they space-time or internal, cannot be directly observed. This conclusion is widely agreed upon, but the reasons given often involve the mistaken view that the introduction of a force is required in order to obtain a local symmetry. Consider the case of local space-time symmetries – arbitrary co-ordinate transformations that leave the explicit form of the equations of motion unaffected. The erroneous argument might be presented as follows. We use Galileo's ship, but this time we compare two states of motion that are in relative acceleration, rather than being in relative uniform motion. In general, we will be able to distinguish between the two states of motion by means of experiments carried out within the cabin of the ship : there is no symmetry. Now, the argument runs, we introduce a force that restores the symmetry, in this case gravity. Kosso, for example[15], writes (using a train rather than a ship) :

> The invariance can be restored by revising the physics, by adding a specific dynamical principle. This is why the local symmetry is a dynamical symmetry. We can add to the physics a claim about a specific force that restores the invariance. It is a force that exactly compensates for the local transform. In the case of the general theory of relativity the dynamical principle is the principle of equivalence, and the force is gravity. (...) With gravity included in the physics and with

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[14] For further details see BRADING and BROWN 2003, where the discussion includes the case of a relative phase transformation between the two beams of the interferometer.

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spacetime symmetries is possible.

The analogous results hold for local internal symmetries[17]. First, neither an arbitrary coordinate transformation in General Relativity, nor a local gauge transformation in locally gauge invariant relativistic field theory, can bring forces in and out of existence : no generation of gravitational effects, and no changes to the interference pattern. Second, local gauge transformations are transformations of both the particle fields and the gauge fields in which the particles are embedded ; no analogue of Galileo's ship experiment, in which a subsystem alone is transformed, can be generated.

3 The indirect empirical significance of symmetries

We have concluded that neither global internal, nor local symmetries — be they spacetime or internal — have direct empirical significance. Where, then, lies the empirical significance of global internal and local symmetries ? All symmetries are properties of the associated laws of motion, and therefore have consequences for the behaviour of systems described by these laws. Some of these consequences can be vividly highlighted by using Noether's theorems. Noether's first (and more famous) theorem connects *global* symmetries (both spacetime and internal) with conservation laws. In this way, global symmetries have *indirect* empirical significance, arising from properties of the laws that are connected to symmetries. This is true for the global space-time symmetries just as much as for the global internal symmetries, and so they too have indirect (in addition to their direct) empirical significance.

Indirect empirical significance arises for local symmetries in exactly the same way. Noether's second theorem is associated with *local* symmetries ; and, with Noether's assistance, Klein derived a third theorem which is again associated with local symmetries. These theorems demonstrate that the restrictions on the possible form of a theory with a given local symmetry are very dramatic. We can use Noether's second theorem to show that not all the equations of motion are independent of one another : this leads to an underdetermination problem in the theory. We can also use these theorems to show the form of the coupling between the matter fields and the gauge fields, what the form of the associated conserved current must be, and so on[18]. The details need not concern

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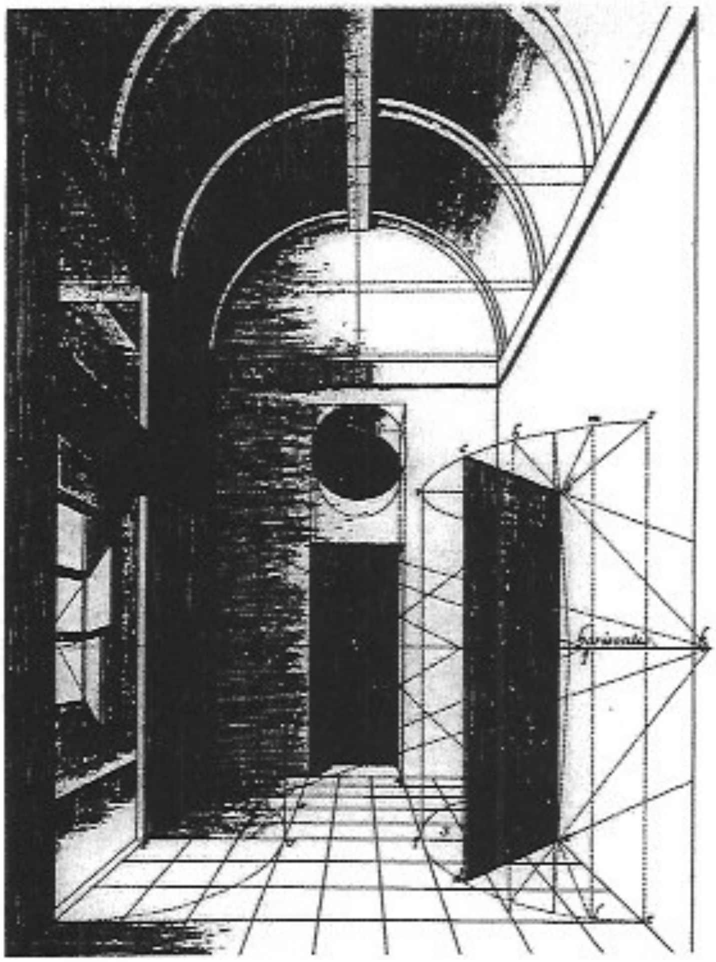
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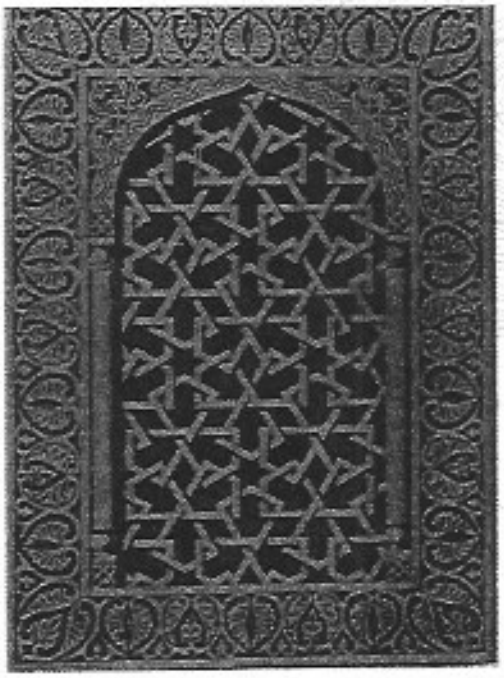

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Where lies the empirical significance of symmetry in physics?[1]

Katherine Brading[*]

Introduction

The first section of this note is about the empirical significance of the familiar continuous symmetries of space and time, and how these symmetries can be directly observed. The second section concerns the claim — and the conclusion — that other symmetries of modern physics (in particular global internal symmetries and local symmetries) cannot be directly observed in this way. This leads to the question of where the empirical significance of such symmetries lies, which is addressed in the final section.

1 Observing the familiar space and time symmetries

Here we are, sitting on Earth, whizzing around the Sun at nearly 67,000 miles per hour, while the Earth itself spins on its axis at about 1000 miles per hour. We all know that the Earth moves, but how can we tell? What are the reasons you would cite for your belief that the Earth moves? Galileo's arguments are well known. On the second day of his *Dialogue Concerning the Two Chief World Systems* he discusses the evidence that was usually given for the view that the Earth must be at rest. He argues that this evidence does not distinguish between the Earth being at rest and the Earth rotating. These negative arguments do not show that the Earth moves, of course, Galileo gave positive arguments for that later in the *Dialogue*. Our interest is in the negative arguments, however, since these give a clear account of what is involved in observing a symmetry.

To make his point, Galileo uses an analogy with the behaviour of objects on a ship. One example is a stone dropped from a tower, which Galileo compares with a stone dropped from the mast of a ship. First, he gives the argument intended to show that the Earth is at rest :

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[1] The presentation given at the meeting was based on Brading and Brown (forthcoming) and this note reproduces the main conclusions of that paper.

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> You say, then, that since when the ship stands still the rock falls to the foot of the mast, and when the ship is in motion it falls apart from there, then conversely, from the falling of the rock at the foot it is inferred that the ship stands still, and from its falling away it may be deduced that the ship is moving. And since what happens on the ship must likewise happen on the land, from the falling of the rock at the foot of the tower one necessarily infers the immobility of the terrestrial globe[2].

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> 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[4].

Galileo's claim is that none of the experiments carried out inside the cabin of the ship, and without reference to anything outside the ship, would enable us to tell whether the ship is at rest or moving across the surface of the Earth. The two states of motion are *empirically indistinguishable* except by appeal to something outside the cabin of the ship : we can't tell whether or not the ship is moving, except by looking out of the porthole. Galileo then claims that, *by analogy*, whether or not the Earth is moving cannot be determined by any of the usual experiments. This is the concept of symmetry in physics that we are interested in, and it is connected to the *unobservability* of certain quantities[5]. The physicist Lee writes :

> The root of all symmetry principles in physics lies in the assumption that it is impossible to observe certain basic quantities[6].

Thus, to observe a symmetry is to observe the unobservable, in the following sense. Galileo's experiment involves two empirically distinct scenarios : the ship at rest with respect to the shore and the ship in motion with respect to the shore. The symmetry is then observed by noticing that, *relative to the cabin of the ship*, the phenomena inside the cabin do not enable us to distinguish between the two scenarios. This has been discussed by Kosso, who writes :

> As long as one can claim to be able to observe that the transformation prescribed by a particular symmetry has taken place, and that the associated invariance held, then one can claim to be able to directly observe the physical symmetry in nature[7].

He goes on :

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[4] 1632, GALILEO, pp.186-187.

[5] Castellani forthcoming, section 2, provides a very clear account of the relationships between symmetry, equivalence, and non-observability. See also CASTELLANI 2003.

[6] LEE 1971, p.308.

[7] KOSSO 2000, p.85.

> To observe the transformation is to observe both the unchanged reference and the changed system[8].

In other words, the first step is to observe the transformation, which involves transforming a subsystem with respect to some reference that is itself observable. Applying the transformation to the subsystem must yield an empirically distinct scenario. The second step is to observe that the symmetry holds for the subsystem of the universe :

> observation of a symmetry will always require two components : One must observe that the specified transformation has taken place, and one must observe that the specified invariant property is in fact the same, before and after[9].

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(1) the move from 'global' continuous symmetries, such as the familiar space-time symmetries we have just mentioned, to 'local' continuous symmetries (of which more below) ; and

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[8] Kosso 2000, p.87.

[9] Kosso 2000, p.86.

(2) the addition of 'internal' symmetries to the spacetime symmetries — this came about with the advent of quantum theory, in which non-spatiotemporal degrees of freedom are attributed to systems.

In this section we consider whether local symmetries and internal symmetries have direct empirical significance in the same way that global spacetime symmetries do. In other words, we ask whether they can be directly observed using an analogue of Galileo's ship experiment.

Consider first the internal symmetries — i.e. symmetries associated with non-spatiotemporal degrees of freedom. Following an article in *Scientific American* by the physicist 't Hooft (1980), several authors have claimed that a global phase transformation is a symmetry transformation, and that it has *direct* empirical significance. The evidence they cite involves the familiar 'two-slits experiment'. In this experiment, a beam of electrons is passed through the two-slit set-up, producing an interference pattern at the screen. We then insert identical phase-shifters into each path, and we notice that the same interference pattern is obtained at the screen. According to 't Hooft[10], Auyang[11], Mainzer[12] and Kosso[13], this constitutes an observation of global phase symmetry, associated with the beam of electrons.

But this is *not* an analogue of the Galileo ship experiment. The reason is that the two states of the beam of electrons are empirically indistinguishable in the following sense : if I give you a system in this state, you will not be able to tell me whether the state is the original or the transformed one. Recall what Kosso said : « observation of a symmetry will always require two components : One must observe that the specified transformation has taken place, and one must observe that the specified invariant property is in fact the same, before and after ». Observing that the specified transformation has taken place means that we must perform the transformation on a subsystem of the universe such that after the transformation has taken place we have an empirically distinct scenarios. This condition is not satisfied by the experiment described by 't Hooft. The original and the transformed states are associated with empirically indistinguishable scenarios. Therefore, this experiment is not an observation of global phase symmetry. More generally, we can conclude that

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[10] 'T HOOFT 1980, pp.98-99.

[11] AUYANG 1995, p.56.

[12] MAINZER 1996, pp.422-423.

[13] KOSSO 2000, p.83.

exact global internal symmetries have no direct empirical significance[14]. This leads to the question : where does the empirical significance of global internal symmetries lie? We will come back to this question in section 3, below.

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It turns out that local symmetries, be they space-time or internal, cannot be directly observed. This conclusion is widely agreed upon, but the reasons given often involve the mistaken view that the introduction of a force is required in order to obtain a local symmetry. Consider the case of local space-time symmetries – arbitrary co-ordinate transformations that leave the explicit form of the equations of motion unaffected. The erroneous argument might be presented as follows. We use Galileo's ship, but this time we compare two states of motion that are in relative acceleration, rather than being in relative uniform motion. In general, we will be able to distinguish between the two states of motion by means of experiments carried out within the cabin of the ship : there is no symmetry. Now, the argument runs, we introduce a force that restores the symmetry, in this case gravity. Kosso, for example[15], writes (using a train rather than a ship) :

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> the windows of the train shuttered, there is no way to tell if the transformation, the acceleration, has taken place. That is, there is now no difference in the outcome of experiments between the transformed and untransformed systems. The force pulling objects to the back of the train could just as well be gravity. Thus the physics, all things including gravity considered, is invariant from one locally transformed frame to the next. The symmetry is restored[16].

But this analysis mixes together the equivalence principle with the meaning of invariance under arbitrary coordinate transformations. We can put the point vividly by locating ourselves at the origin of the coordinate system : I will always be able to tell whether the train, myself, and its other contents are all freely falling together, or whether there is an acceleration of the other contents relative to the train and me (in which case the other contents would appear to be flung around). This is completely independent of what coordinate system I use — my conclusion is the same regardless of whether I use a coordinate system at rest with respect to the train or one that is accelerating arbitrarily.

The two scenarios described are not related by a local spacetime symmetry transformation. In order for a local spacetime transformation to be a symmetry of our theory we must apply it not only to the physical objects appearing in our theory but also to the space-time structure in which those objects are embedded. Active arbitrary co-ordinate transformations in General Relativity involve transformations of both the matter fields *and the metric*, and they are symmetry transformations having no observable consequences. Global symmetry transformations are a special case of local symmetry transformations in which the transformation of the space-time structure reduces to the identity. This means that, just for the case of global symmetry transformations, the link that ties all the physical systems of the universe together — their embedding in spacetime structure — is broken : we can perform a global transformation on a subsystem of the universe without touching the spacetime structure and without touching any of the other physical systems in the universe, and that transformation will still be a symmetry transformation (the new universe will still be a model of our theory). This is what makes Galileo's ship experiment possible in the case of global spacetime symmetry transformations — and it is also why no such direct observation of local

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[16] Kosso 2000, p.90.

spacetime symmetries is possible.

The analogous results hold for local internal symmetries[17]. First, neither an arbitrary coordinate transformation in General Relativity, nor a local gauge transformation in locally gauge invariant relativistic field theory, can bring forces in and out of existence : no generation of gravitational effects, and no changes to the interference pattern. Second, local gauge transformations are transformations of both the particle fields and the gauge fields in which the particles are embedded ; no analogue of Galileo's ship experiment, in which a subsystem alone is transformed, can be generated.

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Indirect empirical significance arises for local symmetries in exactly the same way. Noether's second theorem is associated with *local* symmetries ; and, with Noether's assistance, Klein derived a third theorem which is again associated with local symmetries. These theorems demonstrate that the restrictions on the possible form of a theory with a given local symmetry are very dramatic. We can use Noether's second theorem to show that not all the equations of motion are independent of one another : this leads to an underdetermination problem in the theory. We can also use these theorems to show the form of the coupling between the matter fields and the gauge fields, what the form of the associated conserved current must be, and so on[18]. The details need not concern

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[17] See BRADING and BROWN 2003, for details.

[18] BRADING and BROWN 2003.

us here. The main point is this : the requirement of local symmetry imposes extremely strong restrictions on the possible form of a theory, and it is this that gives local symmetry its indirect — but potentially very powerful — empirical significance.

4 Conclusion

The internal and local continuous symmetries of modern physics are straightforward mathematical generalisations of the global spacetime continuous symmetries. However, the direct empirical significance of global spacetime symmetries *does not* generalise to internal and local symmetries ; it is a very important property that is special to global spacetime symmetries.

Acknowledgements

I am grateful first and foremost to Harvey Brown, with whom the paper on which this note is based was written. I would also like to thank Nicholas Maxwell for our discussions on the observability of internal symmetry transformations, and Patricia Radelet for her invitation to participate in the 'Symétries' meeting.