Symmetries in Physics
Historical-Philosophical Reflections

Elena Castellani
Dipartimento di Lettere e Filosofia
Università di Firenze

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Overview

- **History**

1. Two notions of symmetry
2. Symmetry, equality, equivalence
3. Symmetry principles
4. Symmetry arguments

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  1. Two notions of symmetry
  2. Symmetry, equality, equivalence
  3. Symmetry principles
  4. Symmetry arguments
- **Philosophical reflections**
  5. Symmetries and their functions in science
  6. Interpretations of physical symmetries

1. Two notions of symmetry

Claude Perrault (1613-1688)

LES DIX LIVRES
D'ARCHITECTURE
DE
VITRUVE
CORRIGEZ ET TRADVITS
nouvellement en François, avec des Notes
& des Figures.

A PARIS,
Chez JEAN BAPTISTE COIGNARD,

M. DC. LXXXIV.

C. PERRAULT (1673)

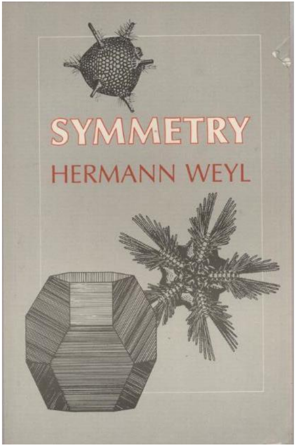
Distinction between two notions of symmetry:

- the *ancient notion*, grounded on proportions relations (Greeks, Latins, Renaissance)

- the *modern notion*, defined as a relation of equality between parts that are opposed

C. Perrault, *Les dix livres d'Architecture de Vitruve, corrigez et traduits nouvellement en françois, avec des notes et des figures*, Paris 1673.

Hermann Weyl (1885-1955)



(1952)

H. WEYL (*Symmetry*, 1952)

"If I am not mistaken the word *symmetry* is used in our everyday language in **two meanings**. In the one sense symmetric means something like well-proportioned, well-balanced, and symmetry denotes that sort of concordance of several parts by which they integrate into a whole. … The image of the balance provides a natural link to the second sense in which the word symmetry is used in modern times: *bilateral symmetry*, the symmetry of left and right …"

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The ancient notion

“La symétrie des anciens”:

- Meaning of the **term** → from the Greek σύν (with, together) and μέτρον (measure), yielding συμμετρία, originally indicating a relation of *commensurability* (in **Euclid**’s *Elements*, Book X: “Those magnitudes are said to be commensurable (σύμμετρα) which are measured by the same measure, and those incommensurable (ἀσύμμετρα) which cannot have any common measure”).

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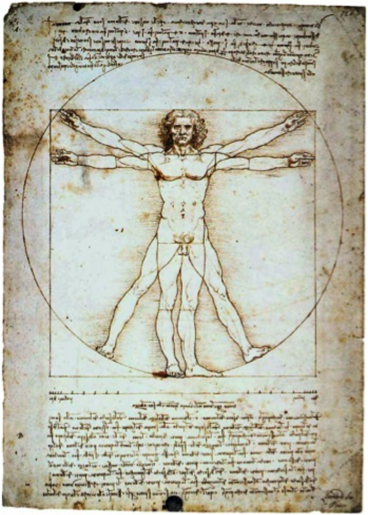
- It quickly acquired a further, more general, meaning → that of (a system of) proportion relations, grounded on (integer) numbers, and with the function of *harmonizing the different elements into a unitary whole*. (Ex: **Vitruvius**' *De architectura*).

Leonardo da Vinci (1452-1519)

Vitruvian Man (around 1460):
Leonardo's drawing of the *Vitruvian proportions* of a man's body inscribed in a *square* and with feet and arms outspread inscribed in a *circle*: a paradigmatic example of an *harmonic ensemble of proportions*.

NOTE: the picture of the human body as a "cosmografia del minor mondo" (cosmography of the microcosm) $\rightarrow$ the proportions of the human body as an analogy for the proportions of the universe.



The modern notion

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The modern notion (Perrault, 1673):

“a relation of **equality** between parts that are opposed”

Alhambra, Granada (Spain)

The modern notion (Weyl, 1952):

"The image of the balance provides a natural link to the second sense in which the word symmetry is used in modern times: **bilateral symmetry**"

From Perrault's modern notion to the (late 18th and early 19th century) crystallographic notion:

Symmetry of a figure: history

From Perrault's modern notion to the (late 18th and early 19th century) crystallographic notion:

- Interpretation of the equality of the parts with respect to the figure as a whole in the sense of their **interchangeability**: equal parts can be exchanged with one another, while preserving the whole.
- Introduction of specific **mathematical operations** (*reflections*, *rotations*, *translations*, and their combinations) in order to describe with precision how the parts are to be exchanged.
- Definition of the **symmetry of a figure** in terms of its *invariance* when equal parts component parts are *exchanged* according to one of these "symmetry operations" or *symmetry transformations* (the kind of symmetry – *reflection symmetry*, *rotation symmetry*, etc. – corresponds to the kind of transformation)

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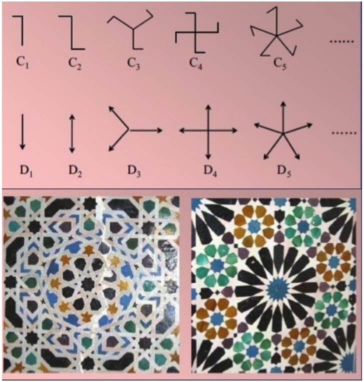
  $\Rightarrow$ crystallographic notion of symmetry (since it was in the context of **early developments in crystallography** that symmetry was first so defined and applied)

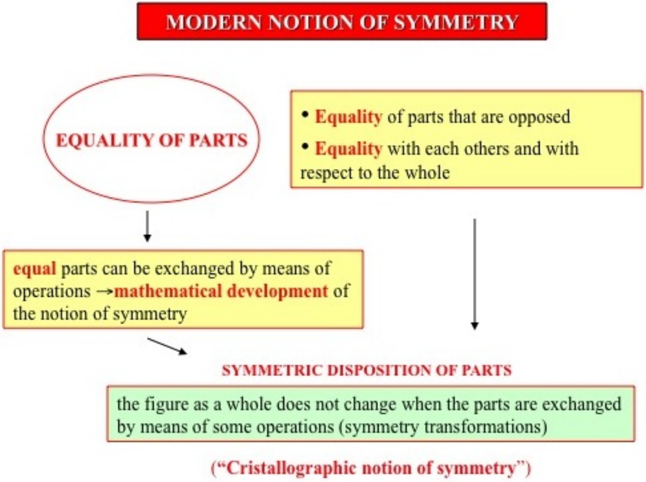
Reflections+Rotations

Snow crystal

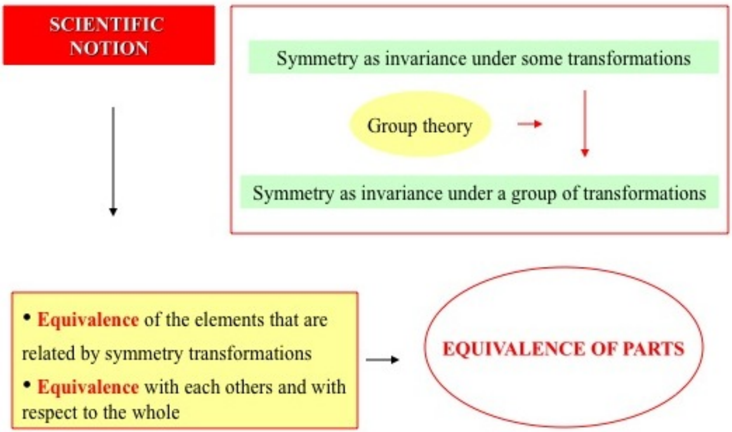


Alhambra’s rosettes

History: “modern notion” → “crystallographic notion”



Generalization to the group-theoretic notion



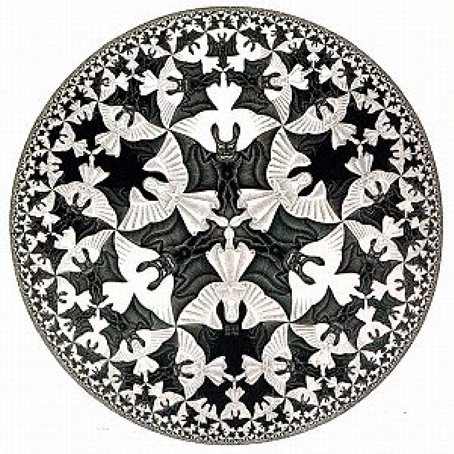
Group-theoretic notion: first steps

- Introduction of the algebraic concept of a group (**Évariste Galois**, 1811-1832) and the following 19th century development of group theory (**Camille Jordan**, **Felix Klein**, **Sophus Lie**,..)

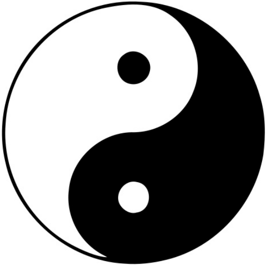
- The symmetry transformations of a figure were found to satisfy the conditions for forming a group (symmetry group of the figure).

- ⇒ Generalization of the theory of symmetry (a systematic classification of all possibile symmetric figures) to other kinds of "spaces" and other kinds of transformations.

  Ref.: **A. V. Shubnikov - V. A.Koptsik** (1974) *Symmetry in Science and Art* (London, Plenum Press)



M. C. Escher (1898-1972)



Yin-Yang

Symmetry in science

$\rightarrow$ the group-theoretic notion of symmetry is the one that has proven so *successful* in modern science:

- Symmetry as invariance under a specified group of transformations allowed the concept to be applied much more widely, not only to *figures* (of external or internal spaces) but also to *abstract objects* such as **mathematical expressions** $\rightarrow$ in particular, expressions of physical relevance such as **dynamical equations.**

Scientific notion

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- **Moreover**: the technical apparatus of group theory could be transferred and used to great advantage within physical theories.

Note: symmetry remains linked to beauty (regularity) and unity.

- Distinct (but equivalent) elements are related to each other and to the whole, thus forming a regular *unity* $\rightarrow$ in the case of the scientific notion, the way in which the *regularity of the whole* emerges is dictated by the nature of the specified transformation group;

$\rightarrow$ thus, a *unity* of *different* and *equal* elements is always associated with symmetry, in its ancient or modern sense:

$\rightarrow$ the way in which this *unity* is realized, on the one hand, and how the equal and different elements are chosen, on the other hand, determines the resulting symmetry and in what exactly it consists.

3. Symmetry principles

Physical symmetries:

- symmetries of laws
  $\rightarrow$ symmetries of physical *equations*
- symmetries of objects (physical systems)
  $\rightarrow$ symmetries of physical *states* (*solutions* of physical equations)

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$\Rightarrow$ **Symmetry principles** (Invariance principles):

- principles postulating the *symmetry properties of physical laws*

  $\rightarrow$ **symmetry transformations** of physical **laws** (/equations):

  - transformations (applied to the equation's variables) that leave the *form of the laws* unchanged.
  - transformations that map *solutions into solutions*.

History

- First *explicit* study and use of the *invariance properties of equations* in physics $\rightarrow$ **transformational approach** to the problem of motion in the *analytic mechanics* of the first half of the nineteenth century (**W.R. Hamilton**, **C. G. Jacobi**, ...).

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- First principle explicitly formulated as an invariance principle → **Einstein's 1905 principle of special relativity** (*invariance of physical laws under the transformation group of inertial reference frames*).
  - **Einstein's work** on *special relativity* marks "**the reversal of a trend**: until then, the principles of invariance were derived from the laws of motion [...] It is now natural for us to derive the laws of nature and to test their validity by means of the laws of invariance, rather than to derive the laws of invariance from what we believe to be the laws of nature" [**Wigner** (1967, 5)]

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- **Afterwards**: GR, application of symmetry group to quantum mechanics and QFT, .. string theory → the history of the application of symmetry groups (and algebras) to physics coincides, in large part, with the history of 'fundamental' theoretical physics

Varieties of physical symmetries

- Space-time symmetries (continuous, discrete, global, and local)
- Permutation symmetry (symmetry under exchange of "identical" quantum particles)
- Charge conjugation (particle-antiparticle symmetry)
- Internal symmetries (global, local ($\rightarrow$ gauge symmetries))
- Supersymmetry (fermion-boson symmetry $\rightarrow$ global [SUSY], local [SUGRA])
- Duality symmetries (electric-magnetic duality, S-duality, T-duality, AdS/CFT, ..)

  ....

Symmetry arguments

Symmetry arguments (s.a.) $\rightarrow$ arguments drawing specific consequences on the grounds of the symmetry properties involved.

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Old examples (of an *implicit use* of s.a.):

- **Anaximander's argument for the immobility of the Earth** (as reported by Aristotle): the Earth remains at rest since, being at the centre of the spherical cosmos (and in the same relation to the boundary of the cosmos in every direction), there is *no reason why* it should move in one direction rather than another.
- **Archimedes's equilibrium law for the balance**: if equal weights are hung at equal distances along the arms of a balance, then it will remain in equilibrium since there is *no reason for it to* rotate one way or the other about the balance point.
- **Buridan's ass**: situated between what are, for him, two completely equivalent bundles of hay, the ass has *no reason to* choose the one located to his left over the one located to his right, and so he is not able to choose and dies of starvation.

Typical form of s.a.: a situation with a certain symmetry evolves in such a way that, *in the absence of an asymmetric cause*, the initial symmetry is preserved.

$\rightarrow$ In other words: a breaking of the initial symmetry *cannot happen without a reason* (suggestion: Leibniz's principle of sufficient reason), i.e. *an asymmetry cannot originate spontaneously*.

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• Historically, the first *explicit use* of a symmetry argument: the so-called **Curie's principle (CP)**.

→ **Curie's CP (slogan)**: *the symmetries of the causes are to be found in the effects.*

P. Curie, 1894

Pierre Curie (1859-1906)

CURIE. — SYMÉTRIE DANS LES PHÉNOMÈNES PHYSIQUES. 393

SUR LA SYMÉTRIE DANS LES PHÉNOMÈNES PHYSIQUES, SYMÉTRIE D'UN CHAMP ÉLECTRIQUE ET D'UN CHAMP MAGNÉTIQUE;

Par M. P. CURIE.

I. Je pense qu'il y aurait intérêt à introduire dans l'étude des phénomènes physiques les considérations sur la symétrie familières aux cristallographes.

Un corps isotrope, par exemple, peut être animé d'un mouvement rectiligne ou de rotation; liquide, il peut être le siège de mouvements tourbillonnaires; solide, il peut être comprimé ou tordu; il peut se trouver dans un champ électrique ou magnétique; il peut être traversé par un courant électrique ou calorifique; il peut être parcouru par un rayon de lumière naturelle ou polarisée rectilignement, circulairement, elliptiquement, etc. Dans chaque cas, une certaine dissymétrie caractéristique est nécessaire en chaque point du corps. Les dissymétries seront encore plus complexes, si l'on suppose que plusieurs de ces phénomènes coexistent dans un même milieu ou si ces phénomènes se produisent dans un milieu cristallisé qui possède déjà, de par sa constitution, une certaine dissymétrie.

Les physiciens utilisent souvent les conditions données par la symétrie, mais négligent généralement de définir la symétrie dans un phénomène, parce que, assez souvent, les conditions de symétrie sont simples et presque évidentes *a priori* (1).

Dans l'enseignement de la Physique, il vaudrait cependant mieux exposer franchement ces questions : dans l'étude de l'électricité, par exemple, énoncer presque au début la symétrie caractéristique du champ électrique et du champ magnétique; on pourrait ensuite se servir de ces notions pour simplifier bien des démonstrations.

Au point de vue des idées générales, la notion de symétrie peut être rapprochée de la notion de *dimension* : ces deux notions fondamentales sont respectivement caractéristiques pour le *milieu*

(1) Les cristallographes qui ont à considérer des cas plus complexes ont établi la théorie générale de la symétrie. Dans les traités de Cristallographic physique (qui sont en même temps de véritables traités de Physique), les questions de symétrie sont exposées avec le plus grand soin. *Voir* les traités de Mallard, de Liebisch, de Soret.

J. de Phys., 3e série, t. III. (Septembre 1894.) 26

Sur la symétrie dans les phénomènes physiques, 1894

Curie's Principle (CP)

First explicit formulation in **P. Curie**, "Sur la symétrie dans les phénomènes physiques. Symétrie d'un champ électrique et d'un champ magnétique", *Journal de Physique* **(1894)**, 3^e série, vol. 3: 393-417.

Curie's motivating question: *Which phenomena are allowed to occur in a given physical medium having specified symmetry properties?*

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Curie's motivating question: *Which phenomena are allowed to occur in a given physical medium having specified symmetry properties?*

Background:

- Curie's studies on the thermal, electric and magnetic properties of crystals (properties related to the structure, and hence the symmetry, of the crystals).
- The methods and results of the theory of symmetry groups used in the **crystallography** of his time.

Curie's conclusions (1)

(a_1) "When certain causes produce certain effects, *the symmetry elements of the causes must be found in their effects*." [CP slogan].

(a_2) "When certain effects show a certain dissymmetry, this dissymmetry must be found in the causes which gave rise to them." [logically equivalent to (a_1)].

(a_3) "In practice, the converses of these two propositions are not true, i.e., *the effects can be more symmetric than their causes*." [asymmetry of CP].

Curie's conclusions (2)

(*b*) "A phenomenon may exist in a medium having the same characteristic symmetry or the symmetry of a subgroup of its characteristic symmetry.

In other words, certain elements of symmetry can coexist with certain phenomena, but they are not necessary.

What is necessary, is that certain elements of symmetry do not exist. **Dissymmetry is what creates the phenomenon**."

$\Rightarrow$ relevance of *symmetry breaking* in physics

Applying CP

Curie's examples:

cases where, by applying CP, conditions are derived for a given phenomenon (the 'effect') to obtain in a medium (the 'cause') .

In such terms $\rightarrow$ CP reads:
the symmetry of the medium cannot be higher than the symmetry of the phenomenon.

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Example:

→ for a **magnetic field** (the effect) to obtain, the *medium* (the cause) must have a symmetry lower or equal to that of a **rotating cylinder**.

(The *characteristic symmetry of a magnetic field* being that of a cylinder rotating about its axis.)

Role of symmetry breaking

CP (in terms of the symmetries of *media* and *phenomena*):

for the **occurrence of a phenomenon in a medium**, the symmetry of the medium cannot be of higher than the symmetry of the phenomenon.

$\Rightarrow$ If not, the symmetry of the medium it must be lowered to the symmetry of the phenomenon

Role of symmetry breaking

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In today's terminology: the *symmetry group* of the medium must be *broken* to the phenomenon's *symmetry group*.

$\Rightarrow$ In this sense, "*symmetry breaking* is what creates the phenomenon".

Conditions *for* applying CP

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In Curie's terminology:

- the cause and the effect must be well-defined;
- the causal connection between them must hold good;
- the symmetries of both the cause and the effect must also be well-defined (this involves both the **physical** and the **geometrical properties** of the physical systems considered).

Conditions *from* applying CP

Modulo the conditions for its application → CP provides a necessary condition for given phenomena to occur:

only those phenomena can happen that are compatible with the symmetry conditions stated by the principle (symmetry constraint).

→ CP has thus an important **methodological function**:

- it furnishes a kind of selection rule (given an initial situation with a specified symmetry, only certain phenomena are allowed to happen);

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- it furnishes a kind of selection rule (given an initial situation with a specified symmetry, only certain phenomena are allowed to happen);
- it offers a kind of *falsification* criterion for physical theories (a violation of Curie's principle may indicate that something is wrong in the physical description).

Discussing CP

Issue: Status and validity of CP

- What sort of principle? (*A priori*? *A posteriori*? *Methodological rule*? *Pragmatic receipt*? *Truism*? *Hazard*?)
- Reducible to another principle? (*Leibniz's principle of sufficient reason*? *Causality principle*? *Determinism & Invariance*?)

FOCUS $\rightarrow$ the philosophical discussion on CP stimulated by the growing interest in the role of symmetry and symmetry breaking in physics.

For example: the validity of the principle has been typically questioned in relation to *spontaneous symmetry breaking*.

Curie's own view

Support for CP → in showing *its* **utility** *in the practice of physics* (*not* in providing *an argument for its validity*).

Curie's focus:

- the *heuristic* aspect of CP
  → what can be obtained, in the prediction of physical phenomena, by means of the relationships between the symmetries of a medium (cause) and the phenomena (effects) occurring in it.

Utility of CP:

→ to "**prevent** us from searching for unrealizable phenomena" ("firm but negative conclusions");

→ to provide "precious **directions** for the discovery of new phenomena" ("positive conclusions, but not offering the same certainty of their results").

General philosophical reflections

Issue $\rightarrow$ *status* and *significance* of symmetries and symmetry principles in physics?

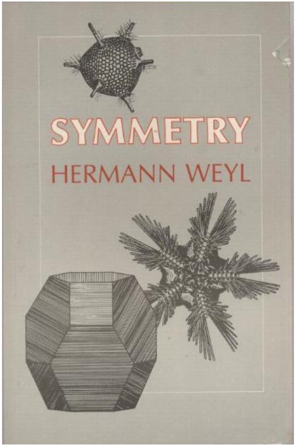
Note $\rightarrow$ exploring the role and meaning of physical symmetries is deeply intertwined with basic questions regarding:

- physical reality $\rightarrow$ ontological aspects of s.
- physical knowledge$\rightarrow$ epistemological aspects of s.
- guiding strategies of physical research $\rightarrow$ methodological aspects of s.

Classic references:

H. Weyl, *Symmetry* (1952) and **E. P. Wigner**, *Symmetries and Reflections* (1967)

Hermann Weyl (1885-1955)



(1952)

E. P. Wigner, 1967

Eugene P. Wigner (1902-1995)

E. P. WIGNER
Symmetries and Reflections
1967

Chapter I

- Invariance in Physical Theory (1949
- Symmetry and Conservation Laws (1964)
- The Role of Invariance Principles in Natural Philosophy (1963)
- Events, Laws of Nature, and Invariance Principles (1964)
- Relativistic Invariance and Quantum Phenomena (1957)
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5. Functions of physical symmetries

Main functions of symmetries in physics:

- **Classificatory** → classification of *physical objects* on the grounds of *symmetry properties*.

  Examples:

  • Crystals → classific. by means of the sym. properties of their *morphology* and *structure*;

  • Elementary particles → classific. by means of the *irreducible representations* of the theory's fundamental symmetry groups (**Wigner** 1939: seminal paper on the *unitary representations of the inhomogeneous Lorentz group*).

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Note: if a classification includes all the *necessary properties* for characterizing a type of entity (for ex: all the *quantum numbers* for a particle type), symmetries may assume a **definitory** function (defining types of entities on the basis of their transformation properties)

$\Rightarrow$ used for a *structural approach* to the entities of modern physics (ex: *group-theoretical account of objects*).

Functions of physical symmetries (2)

- **Classificatory**
- **Normative** $\rightarrow$ symmetries as **constraints** (*restrictions on the form of the dynamical equations* [ex: Einstein's use of *general covariance* for his gravitational equations]; *selections rules*; *Curie's principle*; ..)
- **Unificatory** $\rightarrow$ symmetry groups as a powerful tool for **theoretical unification**: possibility of unifying different interaction theories (gauge theories) by means of the unification of the corresponding symmetry groups (*Grand Unification Theories* [GUTs], *Theory of Everything* , ..)
- **Explanatory**
- **Heuristic**

Functions of physical symmetries (3)

- **Explanatory** $\rightarrow$ many physical phenomena can be 'explained' as (more or less direct) consequences of **(a)** *symmetry principles* or **(b)** *symmetry arguments*.

(a): the explanatory role of symmetries arises from their place in the *hierarchy of the structure of physical theory*.

$\rightarrow$ For ex.: an explanatory role for symmetries with respect to **conservation laws** might be claimed on the basis of Noether's 1918 *connection between symmetries and conservation laws* (along with the more fundamental status of symmetries in the hierarchy).

• **Wigner (1967)** $\rightarrow$ "*This .. the progression from events to laws of nature, and from laws of nature to symmetry or invariance principles, is what I meant by hierarchy of our knowledge of the world around us*".

$\Rightarrow$ Symmetries may be used to explain **(i)** the *form of the laws*, and **(ii)** the *occurrence (or non-occurrence) of certain events* (in a manner analogous to the way in which the laws explain why certain events occur and not others).

Functions of physical symmetries (4)

- Heuristic $\rightarrow$ **methodological** aspects of s. in **guiding** to

• the formulation of **new physical laws**;
• the prediction of the occurrence of **new phenomena** (for ex., *via* Curie's principle);
• the prediction of the existence of **new particles** $\rightarrow$

- *via* the *classificatory role*, on the grounds of vacant places in symmetry classification schemes $\rightarrow$ as in the famous case of the 1962 prediction of the **particle** Ω^- (in the context of the hadronic classification scheme known as the "Eightfold Way").
- *via* the *unificatory role* $\rightarrow$ the paradigmatic example is the prediction of the **W** and **Z particles** (experimentally found in 1983) in the context of the Weinberg-Salam gauge theory proposed in 1967 for the unification of the weak and electromagnetic interactions.
- *via* a *symmetry-based theoretical "mechanism"* $\rightarrow$ the 1964 prediction of the **"Higgs"**, experimentally found in 2012 at LHC.

Natural question: *Why such a role of physical symmetries?*

1. Ontological views $\rightarrow$ symmetries as a *substantial part* of the physical world: the symmetries of theories represent properties **existing in nature**, characterizing the **structure of the physical world**.

Motivations:

- the ontological status of symmetries provides a *reason for their success* in physics (see the successful predictions of new particles);
- the *geometrical interpretation* of spatiotemporal symmetries $\rightarrow$ as symmetries of spacetime itself (the *geometrical structure* of the physical world).

2. Epistemological views → symmetries are seen as being primarily epistemological (→ *conditions*, *modalities* and *limits* in physical inquiry)

Motivations:

(a) Wigner (1967) → the spatiotemporal invariance principles play the role of a **prerequisite** for the very possibility of discovering the laws of nature: "*if the correlations between events changed from day to day, and would be different for different points of space, it would be impossible to discover them*".

→ Two readings:

- **Wigner**: conception related to a fact of *ignorance* (if we could directly know all the laws of nature, we would not need to use symmetry principles in our search for them);
- symmetry principles as *transcendental principles* in the Kantian sense (→ conditions for the possibility of knowledge)

(b) Symmetry and **equivalence** (*irrelevance*, *redundancy*)

(b) Symmetry and **equivalence** $\rightarrow$ *irrelevance*, *redundancy*
the presence of equivalent elements (corresponding to a symmetry) suggests the presence of irrelevant or redundant features in the physical description.

Examples:

- **global spacetime symmetries** $\rightarrow$ the equivalence interpreted in the sense of the irrelevance of "absolute" features. For ex.: *translational symmetry* (equivalence of space points) $\rightarrow$ irrelevance of an *absolute position* to the physical description; ...;
- **local (gauge) symmetries** $\rightarrow$ the irrelevant elements correspond to the presence of "surplus structure" in the theory.

$\rightarrow$ Two readings:

- symmetries as associated with *unavoidable redundancy* in our descriptions of the world (see **Dirac** (1930))
- symmetries as indicating a *limitation* of our epistemic access $\rightarrow$ there are certain properties of objects, such as their absolute position, that are *not observable* (T. D. Lee, 1981)

SYMMETRY, EQUIVALENCE, IRRELEVANCE

SYMMETRY GROUP → PARTITION INTO EQUIVALENCE CLASSES

↓

elements connected to each others by symmetry transformations form an equivalence class

In Physics:

how to interpret the presence of equivalent elements?

- **EQUIVALENCE → IRRELEVANCE**

the presence of a symmetry (equivalent elements) corresponds to the presence of irrelevant features in the theory

> **"[Nature's] fundamental laws control a substratum of which we cannot form a mental picture without introducing irrelevancies.**
> **The formulation of these laws requires the use of the mathematics of transformations." (P.A.M. Dirac, 1930)**

- **IRRELEVANCE → NONOBSERVABILITY**

irrelevant theoretical features make no observable difference

> **"The root of all symmetry prinicples lies in the assumption that it is impossible to observe certain basic quantities." (T.D. Lee, 1981).**

4. Connection between symmetry and objectivity → on either an *ontological* or an *epistemological* account.

Starting point → once again by spacetime symmetries: the laws by means of which we describe the evolution of physical systems have an *objective validity* because they are the same for all observers.

→ The old and natural idea that *what is objective should not depend upon the particular perspective* under which it is taken into consideration is thus reformulated in the following *group-theoretical terms*:

objective is what is invariant with respect to the transformation group of reference frames.

Symmetry and Intersubjectivity

SPACETIME SYMMETRIES

↓

equivalence of reference frames

→

condition of objectivity
(intersubjective validity)
for
a physical description in terms of laws

↑ ↓

common idea

(SYMMETRY GROUPS)

↓

what is objective
should not depend upon a
particular perspective

←

"Objectivity means invariance with respect to the group of automorphisms [of spacetime]"

H. WEYL (*Symmetry*, 1952)

Symmetry and Objectivity

(Physical) Symmetries — Constitution of (Physical) Objectivity

↓

SYMMETRY GROUPS
GROUP REPRESENTATIONS
EQUIVALENCE CLASSES

↙ ↘

SYMMETRIES and INTER-SUBJECTIVITY	**SYMMETRIES and OBJECTS**

Summing up

- Symmetries in physics offer various *interpretational options*.
- The position that one takes will depend in part on one's preferred approach to other issues in philosophy of science $\rightarrow$ *scientific realism*, the *laws of nature*, the *relationship between mathematics and physics*, the nature of *theoretical entities*, ...
- It will also depend on whether one views symmetries as ultimately *fundamental* or *derivative* (be that in a methodological sense or in an ontological sense).

$\Rightarrow$ How to understand the status and significance of physical symmetries clearly presents a challenge to both physicists and philosophers.

Summing up

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⇒ How to understand the status and significance of physical symmetries clearly presents a challenge to both physicists and philosophers.

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Thank you!