Symmetry Breaks Out —
A Fundamental Concept Jumps Over Disciplinary Barriers
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Energy and conceptual change

There are many ways and different motivations to do research in the history of science. An approach of much interest to philosophers and cognition scientists focuses on the historical genesis and consolidation of conceptual changes.

Theories are continuously modified to meet the challenges of unexplained facts in new areas of experience opened by the invention of new instruments and the concomitant expansion of theoretical perspectives.

**Conceptual change**: Creation of new concepts and replacement of old concepts with modified or generalized versions. Conceptual change proceeds often in gradual and incremental fashion, but at times it turns dramatically abrupt during the course of revolutionary episodes, such as those that Thomas Kuhn characterized as “paradigm shifts”.
In this presentation I sketch some highlights in the careers of the concepts of *energy*, *symmetry* and *symmetry breaking*, concentrating on their role as **unifying conceptions of an exceptionally deep and overarching character**.

I try to show how their **generalizing** and **unifying** explanatory power relates to their capacity for connecting previously isolated fields of inquiry, first in physics and later in chemistry and biology.
Three principal and consecutive stages

1.- Establishment of the principle of conservation of energy as “the highest law in all science” in the second half of the 19th century.

2.- Emergence of the concept of symmetry — in terms of invariance with respect to physical and mathematical transformations — as the most fundamental conception in the first half of the 20th century.

3.- Rise of the concept of symmetry breaking in the second half of the last century.

Twelve scientists and engineers working largely independently came close to a full understanding of our current concept of energy and its conservation.

In the first half of the nineteenth century there were at least four separate lines of research that eventually converged at midcentury into the mature, operational concept of energy propounded by Lord Kelvin.
This approach required the invention of invisible, "imponderable" fluids: electrical, magnetic, caloric, etc.

Among the main researchers: George Green (1793-1841), Carl Gauss (1777-1855).

They developed ideas stemming from Leibniz’s conception of kinetic energy as *vis viva*. 
This tradition which included experimenters such as Borda (1733-1799), Coulomb (1736-1806) and Faraday (1791-1867), sought to describe quantitatively the interactions and transformations of hypothetical fluids by developing sophisticated instruments and measuring techniques.

Their work led to a vague but almost universal conviction of the reciprocal and universal interconversion of the “forces of nature.”
In France a third and most important research line included a new brand of engineer-scientists that flourished under novel institutions, like the École Polytechnique. Their efforts, best exemplified by those of Sadi Carnot (1796-1832), were directed at measuring and improving the efficiency of steam engines.

In Great Britain, engineer-scientists such as Joule (1818-1889), Lord Kelvin (1824-1907) and Rankine (1820-1872), followed a similar approach. Their investigations led them naturally to the central concept of work, which they expressed under such rubrics as "mechanical effect."
III. On the Mechanical Equivalent of Heat. By James Prescott Joule, F.C.S.,
Sec. Lit. and Phil. Society, Manchester, Cor. Mem. R.A. Turin, &c. Communicated
by Michael Faraday, D.C.L., F.R.S., Foreign Associate of the Academy
of Sciences, Paris, &c. &c. &c.

Received June 6.—Read June 21, 1849.

"Heat is a very brisk agitation of the inessential parts of the object, which produces in us that sensation
from whence we denominate the object hot; so what in our sensation is heat, in the object is nothing but
motion."—Locke.

"The force of a moving body is proportional to the square of its velocity, or to the height to which it would
rise against gravity."—Leibnitz.

In accordance with the pledge I gave the Royal Society some years ago, I have now
the honour to present it with the results of the experiments I have made in order to
determine the mechanical equivalent of heat with exactness. I will commence with
a slight sketch of the progress of the mechanical doctrine, endeavouring to confine
myself, for the sake of conciseness, to the notice of such researches as are imme-
diately connected with the subject. I shall not therefore be able to review the valu-
able labours of Mr. Forbes and other illustrious men, whose researches on radiant
heat and other subjects do not come exactly within the scope of the present memoir.

For a long time it had been a favourite hypothesis that heat consists of "a force or
power belonging to bodies*;" but it was reserved for Count Rumford to make the first
experiments decidedly in favour of that view. That justly celebrated natural philos-
opher demonstrated by his ingenious experiments that the very great quantity of heat
excited by the boring of cannon could not be ascribed to a change taking place in the
calorific capacity of the metal; and he therefore concluded that the motion of the
boring was communicated to the particles of metal, thus producing the phenomena of
heat:—"It appears to me," he remarks, "extremely difficult, if not quite impossible,
to form any distinct idea of anything, capable of being excited and communicated,
in the manner the heat was excited and communicated in these experiments, except
it be motion†.

One of the most important parts of Count Rumford's paper, though one to which

* Crawford on Animal Heat, p. 15.
† "An Inquiry concerning the Source of the Heat which is excited by Friction." Phil. Trans. Abridged,
vol. xviii. p. 286.
In Germany, researchers reached the conception of the conservation of energy via physiological considerations, in the work of Mayer (1814-1878) and Helmholtz (1821-1894).
In 1851 Rankine formally introduced the concept of **potential energy** as the work stored in the configuration of a system.

Once the relations between **work**, **kinetic energy** and **potential energy** became defined in both **mathematical** and **instrumental** terms, Kelvin was able to articulate the concept of energy as we understand it at present, where the fact of its conservation is known as the **first law of thermodynamics** (“energy cannot be created or destroyed”).

By W. J. Macquorn Rankine.

Actual, or Sensible Energy, is a measurable, transmissible, and transformable condition, whose presence causes a substance to tend to change its state in one or more respects. By the occurrence of such changes, actual energy disappears, and is replaced by Potential or Latent Energy; which is measured by the product of a change of state into the resistance against which that change is made.

(The six senses of matter in motion, thermometric heat, radiant heat, light, chemical action, and electric currents, are forms of actual energy; amongst these of potential energy are the mechanical powers of gravitation, elasticity, chemical affinity, statical electricity, and magnetism.)

The law of the Conservation of Energy is already known, viz.:—that the sum of all the energies of the universe, actual and potential, is unchangeable.

The object of the present paper is to investigate the law according to which all transformations of energy, between the actual and potential forms, take place.

Let \( V \) be the magnitude of a measurable state of a substance;

\( U \), the species of potential energy which is developed when the state \( V \) increases;

\( P \), the common magnitude of the tendency of the state \( V \) to increase, and of the equal and opposite resistance against which it increases; so that

\[ dU = P dV \]

\[ P = \frac{dU}{dV} \quad (A) \]

Let \( Q \) be the quantity which the substance possesses, of a species of actual energy whose presence produces a tendency of the state \( V \) to increase.

It is required to find how much energy is transformed from the actual form \( Q \) to the potential form \( U \), during the increment \( dV \); that is to say, the magnitude of the portion of \( dU \), the potential energy developed, which is due to the disappearance of an equivalent portion of actual energy of the species \( Q \).

The development of this portion of potential energy is the immediate effect of the presence in the substance of the total quantity \( Q \) of actual energy.

Let this quantity be conceived to be divided into indefinitely small equal parts \( dQ \). As those parts are not only equal, but altogether alike in nature and similarly circumstanced, their effects must be equal; therefore, the effect of the total energy \( Q \) must be equal simply to the effect of one of its small parts \( dQ \), multiplied by the ratio \( \frac{Q}{dQ} \).
Transdisciplinary generalization and unification

Towards the end of the nineteenth century, energy brought together under a single explanatory umbrella previously unrelated phenomena and theories, including mechanics, electromagnetism and heat.

Energy considerations opened up entirely new vistas in biology (e.g., the role of photosynthesis, respiration and metabolism) and in chemistry (e.g., endothermic and exothermic reactions).
Symmetry, invariance, and conceptual change

**Symmetry**: the property of a process, system or law that remains **invariant** under a group of operations or transformations. Analogously to the case of energy in the second half of 19th century physics, *symmetry rose to the status of a supreme unifying and explanatory notion in the first half of 20th century physics.*
Epistemological shift

Symmetry’s unparalleled role in contemporary physics came about through an unprecedented epistemological move, first fully manifested in Einstein’s creation of the special theory of relativity in 1905.

This shift consisted in turning one’s attention away from the usual business of finding invariances in the phenomena (the discovery of laws) to a consideration of the symmetries displayed by the laws themselves.
Special relativity (Einstein, 1905)

An essential ingredient was the replacement of Galilean invariance, which tacitly depends on absolute simultaneity, with global Lorentzian invariance, which belongs to a more general group of transformations under which simultaneity becomes relative to the state of motion of a body or system.

The most basic postulate of this theory is the invariance of the laws of physics with respect to changes in inertial (non-accelerated) frames of reference.
General theory of relativity (Einstein, 1915)

The general theory of relativity is based on a more general kind of symmetry (general covariance) and has as a basic postulate that the laws of nature are invariant with respect to all frames of reference (not just inertial ones).

The symmetries involved in classical dynamics and special relativity are global (invariances under transformations at all spacetime points).

Local symmetries (invariances under transformations that change at different spacetime coordinates) were to enjoy an even more decisive status in all branches of twentieth century physics.
Symmetry and energy

Emmy Noether’s celebrated theorem in 1918 marked a momentous event in the relations of the concepts of energy and symmetry. In non-technical terms, it states that every continuous global symmetry of the laws of nature entails the existence of a characteristic conserved quantity. For instance, the invariance of the laws of dynamics under space translations entails the conservation of linear momentum. Similarly, their invariance under a time translation entails the conservation of energy. So it turns out that the conservation of energy, the conceptual cornerstone of nineteenth century physics, becomes in the twentieth century a mere corollary of one of the global symmetries of the laws of nature.
Nachrichten
von der
Königlichen Gesellschaft der Wissenschaften
zu Göttingen.

Mathematisch-physikalische Klasse
aus dem Jahre 1918.

AMERICAN ACADEMY
MAR 24 1924
OF ARTS AND SCIENCES

Berlin,
Weidmannische Buchhandlung.
1918.

Invariante Variationsprobleme.
(F. Klein zum fünfzigjährigen Doktorjubiläum.)
Von
Emmy Noether in Göttingen.


Es handelt sich um Variationsprobleme, die eine kontinuierliche Gruppe (im Lieschen Sinne) gestatten; daraus sich ergebende Folgerungen für die zugehörigen Differentialgleichungen finden ihren allgemeinsten Ausdruck in den in § 1 formulierten, in den folgenden Paragraphen bewiesenen Sätzen. Über diese aus Variationsproblemen entspringenden Differentialgleichungen lassen sich viel präzisere Aussagen machen als über beliebige, eine Gruppe gestattende Differentialgleichungen, die den Gegenstand der Lieschen Untersuchungen bilden. Das folgende beruht also auf einer Verbindung der Methoden der formalen Variationsrechnung mit denen der Lieschen Gruppentheorie. Für spezielle Gruppen und Variationsprobleme ist diese Verbindung der Methoden nicht neu; ich erwähne Hamilton und Herglotz für spezielle endliche, Lorentz und seine Schüler (z. B. Fokker), Weyl und Klein für spezielle unendliche Gruppen. Insbesondere sind die zweite Kleinische Note und die vorliegenden Ausführungen gegeneinander durch einander beein-

1) Die endgültige Fassung des Manuskriptes wurde erst Ende September eingereicht.


In einer eben erschienenen Arbeit von Kneser (Math. Zeitschrift Bd. 2) handelt es sich um Aufstellung von Invarianten nach ähnlicher Methode.
Gauge invariance

A special kind of local symmetry, gauge invariance, was of paramount importance in the development of quantum theory and the subsequent creation of the Standard Model of particle physics. This model is based in the realization that the fundamental forces of nature arise from constraints imposed by gauge symmetries on the laws of nature.

In 1918, in the year that saw the publication of Noether’s theorem, Hermann Weyl (1885-1955) discovered the idea of gauge invariance and introduced it in an unsuccessful attempt at unifying gravitation and electromagnetism. In the 1920’s Weyl and Eugene Wigner (1902-1995) were among the first physicists to realize the extraordinary power of symmetry considerations for the development of quantum theory.
Symmetry breaking

In the second half of the twentieth century the notion of **symmetry breaking** has risen to center stage, jumping over remotely separated disciplines: condensed matter physics, quantum chromodynamics, cosmology, economics, computer programming... even string theory and biological evolution.

The easiest way to understand symmetry breaking is through the example of its occurrence in **phase transitions**.
Phase transitions

**Example:** Water exists ordinarily in one of three phases: solid, liquid or vapor. The relations between them depend on temperature and pressure.

Consider an ice cube floating in a glass of water. As the temperature increases the ice melts into liquid water and liquid water evaporates. The transitions from one phase to another are marked by abrupt discontinuities in water density. There are **critical values** of the temperature at which these discontinuities occur, such as the freezing point or the boiling point.

These discontinuities mark a **breaking of symmetry**. The liquid phase is more symmetric than the solid state. In liquid water all directions are equivalent (rotational invariance) but ice has a crystal structure with preferred directions, and the **rotational symmetry is broken**.
Curie’s principle

In a 1894 article Pierre Curie first noted and analyzed the phenomenon of symmetry breaking.

Curie’s principle states that the occurrence of a new phenomenon in a medium indicates that the original symmetries of the medium have been reduced to those displayed by the phenomenon. Such reduction of symmetry creates the phenomenon.
JOURNAL
DE PHYSIQUE
THÉORIQUE ET APPLIQUÉE,

PAR J.-CH. D’ALMEIDA

ET PUBLIÉ PAR
MM. E. BOUTY, A. CORNU, E. MASCART, A. POTIER.

TROISIÈME SÉRIE.
TOME TROISIÈME. — ANNEE 1894.

PARIS,
AU BUREAU DU JOURNAL DE PHYSIQUE.
11, RUE BATAUD, 11.
1894

CURIE. — SYMÉTRIE DANS LES PHÉNOMÈNES PHYSIQUES,
SÉMÉTRIE D’UN CHAMP ÉLECTRIQUE ET D’UN CHAMP MAGNÉTIQUE;
PAR M. P. CURIE.

1. Je pense qu’il y aurait intérêt à introduire dans l’étude des
phénomènes physiques les considérations sur la symétrie famil-
lières aux cristallographes.

Un corps isotrope, par exemple, peut être animé d’un mouve-
ment rectiligne ou de rotation; liquide, il peut être le siège de
mouvements tourbillonnaires; solide, il peut être comprimé ou
touré; il peut se trouver dans un champ électrique ou magnétique;
it peut être traversé par un courant électrique ou calorifique;
it 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
echaque point du corps. Les dissymétries seront encore plus com-
plexes, si l’on suppose que plusieurs de ces phénomènes coexis-
tent 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
daus un phénomène, parce que, assez souvent, les conditions de
symétrie sont simples et presque évidentes a priori (**).

Dans l’enseignement de la Physique, il vaudrait cependant mieux
n’exposer franchement ces questions : dans l’étude de l’électricité,
pour 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

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

J. de Phys., 3e série, t. III. (Septembre 1894)
Symmetry breaking and unification

Since the 1960s the notion of symmetry breaking has unified the once remote disciplines of particle physics and cosmology. Through the Standard Model it explains the emergence of the various fundamental particles and simultaneously unify the fundamental forces of nature. The mechanism that explains the generation of the particles by successive symmetry breakings also explains the formation of the early universe.

Because of symmetry breakings, the basic forces of nature have very different characteristics at the low energies prevalent in the present cosmic epoch. But at the high energies (temperatures) of the early universe they are expected to merge into a single force complying with a postulated supersymmetry.
To conclude

In this brief sketch I have tried to highlight the ascendancy of concepts toward increasing generality and unification through the most dramatic example I could find, the route from energy to symmetry breaking.

Similar narratives exist for other important concepts, and more are waiting to be unearthed.

An inventory of case histories of concept evolution can be of great interest not only to cognition scientists and philosophers of science, but also to those who want to inject historical depth into the teaching of scientific ideas and methods.

_Maurits Cornelius Escher_
Tyger, tyger burning bright,
In the forests of the night,
What immortal hand or eye
Could frame thy fearful symmetry?

--William Blake