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FROM THE "ELECTRON AS A CATALYST" CONCEPT TO A NEW PARADIGM OF CATALYSIS

***Abstract.** The article proposes a new paradigm of catalysis. It is developed as a natural continuation of the advanced concepts in catalysis, such as "electron as a catalyst", "proton as a catalyst", and "oxidation state concept". The goal of the new catalysis paradigm is to reveal the general mechanism of catalytic reactions and to derive the laws of catalysis. The new paradigm of catalysis is based on the idea that two universal catalysts exist in nature that can increase the reactivity of chemical substances. The catalysts in all types of catalysis are fundamental objects of the microcosm - elementary particles: the electron and the proton. In the new paradigm, numerous substances that have traditionally been considered catalysts are assigned the role of precursors of catalysts. In the reaction, they mediate the transfer of electrons and protons. The common mechanism in various types of catalysis is a mechanism based on the transfer of electric charges by electrons and protons and on the change in the oxidation state of the reactants with their participation. Changing the state of oxidation of reactants, the formation of radicals leads to an increase in their reactivity. A model of the relay donor-acceptor mechanism as a universal mechanism of catalysis was proposed. The new paradigm of catalysis has made it possible to reveal the universal mechanism of catalytic reactions and to solve the main problem of catalysis - to obtain a single universal law of catalysis. From the universal law of catalysis, the laws of heterogeneous, homogeneous, field catalysis, and Faraday's law of electrolysis follow as particular results. The laws of catalysis are represented not by empirical equations, but by mathematical relations in which the parameters are chemical and physical characteristics of the catalyst, precursor, and reagents. The new paradigm shows that catalysis is a universal and fundamental natural phenomenon. The concept of two fundamental catalysts leads to the conclusion that all chemical reactions are catalytic. They are realized by a single universal mechanism of catalysis. In those reactions that are carried out without the presence of additional substances and are not traditionally considered catalytic, the catalysts are an electron or a proton. In these reactions, one of the reactants plays the role of a precursor and a donor of elementary particles.*

***Keywords:** new paradigm of catalysis, "electron as a catalyst" concept, catalysis induced by electrons, catalysis induced by protons, concept of two fundamental catalysts, relay donor-acceptor mechanism of catalysis, laws of catalysis, universal law of catalysis, oxidation states.*

1. Introduction

The history of catalysis shows that many fundamental discoveries in catalysis were made either by chance or empirically by enumerating a large number of substances in extensive and expensive experiments. There is still no understanding of which characteristics of a catalyst determine its catalytic properties. There is no understanding of what characteristics of the substance of catalysts affect the rate of catalytic reactions [1, 2].

Attempts to solve the mystery of the catalytic phenomenon have been undertaken by scientists throughout the history of catalysis. Nevertheless, the mechanisms of catalysis are still largely a mystery. Catalysis is still highly dependent on experience and has not yet turned from a method of trial and error to a science based on a rational design [3, 4].

Scientists do not abandon the belief that different types of catalysis are based on the same principles. [5]. At the same time, the common features of catalytic reactions in different types of catalysis remain undisclosed. It cannot be considered normal that in its two-century history, it has not been possible to create a general theory of catalysis and to discover the laws of catalysis. This "lawlessness" in catalysis has dragged on too long.

In recent years, new catalytic phenomena have been discovered, and promising ideas have emerged in catalysis theory that have the potential to lead to revolutionary changes in the science of catalysis. These include:

- a) catalysis without the participation of transition metals under the action of electrons and the concept of "electron as a catalyst" [6];
- b) catalysis under the action of an electric field without the participation of material catalysts and the concept of "electric field as a catalyst" [7, 8, 9, 10];
- c) the concept of the oxidation state in catalysis [11, 12];
- d) the discovery of dynamic catalysis, the discovery of catalytic resonance, and overcoming the Sabatier limitation for catalysts [13, 14 -18, 19].

The concept of "electron as a catalyst" and the concept of "electric field as a catalyst" become a challenge to the modern paradigm of catalysis and the modern understanding of the nature of catalysis [9, 20, 21, 22].

The development of these concepts can lead to the revision of the modern concept of catalysis and to the creation of a new paradigm of catalysis. This gives hope for solving the mystery of catalysts and the mystery of the mechanism of catalysis. There is hope that it will be possible to take the science of catalysis beyond empiricism and learn how to control catalysts.

2. The concept of "electron as a catalyst"

The assumption that electrons take part in catalytic processes was made by Ostwald 90 years ago [23]. Ostwald drew attention to the fact that good catalysts are good conductors of electricity and easily give up electrons from their surface. Those catalysts that have the property of electron emission show high catalytic activity [23]. Similar ideas about the role of electrons in catalysis were expressed about 85 years ago by L. V. Piszhevsky [24 - 26]. S. Z. Roginsky [27] pointed out the mechanism of catalysis, in which the important role is assigned to the transfer of electrons. Hauff [28], Dowden [29], and Volkenshtein [30] further developed the idea of the electronic mechanism of catalysis. They attempted to create an electronic theory of catalysts [28 - 30].

Currently, the field of catalysis has accumulated many examples of catalytic reactions where electrons act as catalysts [31 - 36]. Catalysis by hydrated electrons is a prime example of catalytic reactions without the use of catalysts. The high reducing potential (-2870 mV) of the hydrated electrons obviously acts as the main acting factor in the catalytic reaction [36]. Electron transfer between catalyst and reactants is one of the main features in catalytic reactions. As noted in [37], "any factor affecting the ability to give or receive electrons by the reactants can be considered to influence catalytic activity.

Electron transfer in catalysis is demonstrated by metal-free organic catalysts. A new idea has been implemented in the design of organocatalysts: instead of a metallic active center, an organic active center capable of giving and receiving electrons has been synthesized [38, 39].

In [40] it was suggested that the electron or hole, like the proton, can act as very effective catalysts. In enzymatic catalysis, there is convincing evidence that electrostatic effects provide the greatest catalytic contribution [41 - 43].

A real breakthrough in the understanding of the role of electrons in catalysis was the "electron as a catalyst" concept. This concept was introduced in 2014 by Studer A., Curran D. [6, 44]. The electron was assigned to a class of catalysts similar to the proton, which has long been considered a catalyst in homogeneous catalysis. The electron has been shown to be an effective catalyst for various types of radical cascade reactions, which proceed via intermediate radicals and radical ions. Electrons can be supplied by electric current, injection, or reducing compounds [45, 46]. Scientists are working to make electron-mediated catalysis an independent field of research in organic synthesis [47]. Judging by the large number of publications, the development of the "electron as a catalyst" concept is becoming a very promising area of research in catalysis [47, 48, 49, 50, 51].

New reactions that are catalyzed by electrons and new ideas about the role of electrons in catalysis can initiate a revision of catalysis mechanisms and even affect catalysis terminology. Accepting the electron-catalyst concept, it should not be assumed that the electron is complementary to the family of known catalysts. It should not be assumed that the electron is "another catalyst" in the numerous family of catalysts. This is because the status of the electron is different from that of other catalysts. The electron does not belong to the class of chemical substances, In physics, the electron is considered a fundamental particle of the microcosm. The fundamental object in the family of elementary particles does not fit in the same row as the chemical elements. Its role in the mechanism of catalysis is more significant than that of other catalysts. The interaction of the electron-catalyst with the reactants is not a chemical reaction. It is an interaction on the level of elementary particles. With the appearance of the electron as a catalyst in catalysis, the contradictions of the modern concept of catalysis are exposed. The question of revising the modern concept of catalysis and the mechanism of action of catalysts becomes acute.

3. The concept of "electron and hole as catalysts"

Hole catalysis is seen as the inverse of electron catalysis. In the initiation step, the electron is taken away from the substrate rather than added. This means creating a hole in the valence shell of the substrate [52 - 58]. Both the additional electron and the corresponding hole exhibit catalytic effects. Electron-hole catalysis is becoming a burgeoning field of research. Recent advances in the application of electron-hole catalysis show the high potential and versatility of this strategy in all aspects of modern chemistry [52 - 58].

4. The concept of "proton as a catalyst"

The proton has long been considered a common homogeneous catalyst [59-65]. The phenomenon of catalysis by protons is interpreted as the electrostatic interaction of the proton with the reactants. The model of proton-donor-acceptor interaction of the catalyst and reactants was first proposed by Thomas Martin Lowry in 1925 - 1928. He formulated the idea of the proton-donor-acceptor mechanism as applied to homogeneous catalytic processes. According to Lowry, homogeneous catalysis is caused by the alternating interaction of a reagent molecule with a catalyst.

The mechanism consists of the reactant attaching a proton received from the donor catalyst and then transferring the protons to the catalyst-acceptor [66, 67].

The proton, like the electron, should not be considered "another catalyst" that complements the family of known catalysts. The status of the proton is different. It does not belong to the class of chemical substances. In physics, the proton is considered a fundamental particle of the microcosm. Interaction of the proton with reagents is an interaction at the level of elementary particles. Unfortunately, these features of the proton are not given proper attention in studies of catalysis. The proton is traditionally considered one of the catalysts in the family of other catalysts [61] and is even referred to reagents [68].

With the appearance of fundamental particles (electron and proton) in the role of catalysts in catalysis, the contradictions in the science of catalysis have become more acute. The question of revising the current concept of catalysis is acute. First of all, this applies to a different kind of interaction of the catalyst-electron and catalyst-proton with the reactants. This is not an interaction of chemicals. It is the interaction of elementary particles with chemical substances. The main feature of this interaction is its fundamental nature.

Proton and electron have a lot in common. Both protons and electrons carry equal electric charges ($e = 1.602\ 176\ 634 \times 10^{-19}$ C). The electron and proton have a fundamental status in the family of elementary particles. The electric charge of one mole of electrons and one mole of protons is represented by the fundamental constant, the Faraday constant ($F = 96485.3321233100184$ C/mol). The interaction in which the electron and proton participate is electrostatic. It is one of the four fundamental interactions in nature.

The acceptance of the concepts "electron as a catalyst" and "proton as a catalyst" creates a new situation in the science of catalysis. Deep contradictions in this science are exposed. The fundamental status of the electron and proton does not allow us to place them on the same level with chemical substances. Therefore, it is not necessary to consider them ordinary catalysts on a par with other catalysts. It is logical to consider these particles not as additions to the family of known catalysts, but as special catalysts. It is logical to apply to them the principle: "not together with other catalysts, but instead of them".

5. The "electric field as a catalyst" concept

Even more contradictions are exposed in the modern paradigm of catalysis with the appearance of an electric field as a catalyst in the family of catalysts. The practice of catalysis shows that the variety of catalysts is not limited to material catalysts. A non-material object, a field, can also act as a catalyst. More and more studies are appearing in which an electric field is considered to be a catalyst for chemical reactions [69 - 115]. More and more researchers conclude that "electric fields open up a new way to catalyze chemical reactions." [72 - 84]. The electric field is sometimes categorized as a class of reagents and is referred to as a "smart reagent" [93]. Recently, the number of works investigating the role of electric fields in catalysis has increased dramatically. The key role of the electric field in various types of catalysis has been revealed [108, 109, 110]. A new trend based on the use of electric fields instead of material catalysts is forming in catalysis, and a new type of catalysis, electric field catalysis, has emerged in chemistry [7, 8, 82, 104, 105].

In addition to the direct action of an external field on the reactants and on the catalyst, the influence of internal electric fields on catalytic activity and selectivity has been revealed [71, 79, 101]. Since spontaneous electric fields are present in all types of catalysis, it was concluded in [79] that electrostatic phenomenology can be inherent in all types of catalysis. The use of intermolecular

electrostatic interaction to turn on and off the reactivity of substances has great promise in catalysis [106].

The classification of fields as catalysts forces a radical revision of the modern concept of catalysis and the search for new explanations of the mechanism of catalytic reactions. The generally accepted mechanism of catalysis, based on the formation of intermediate compounds between the catalyst and the reactants, is not suitable for explaining the mechanism of field catalysis.

Can the field be considered as another catalyst that complements the already large family of known catalysts? To get the answer, let us list the important features of the field:

1. The field, unlike other catalysts, is a fundamental physical object;
2. The interaction of the field with matter does not refer to chemical interaction;
3. The field is not a substance;
4. The field cannot form intermediate compounds with reagents.

As we can see, it is difficult to find a place for the electric field in the current paradigm of catalysis. The electric field does not fit into the family of real catalysts at all, as an addition to this family. It cannot be put on a par with the known substance catalysts. The field cannot be considered either a reagent or "another catalyst". The place of the field in catalysis has yet to be determined.

6. The concept of the oxidation state in catalysis

The history of the oxidation state concept goes back about 200 years [116 - 118]. Although the oxidation state of substances is widely used in chemistry, it is considered to be an auxiliary conventional value that has no physical meaning [119 - 122]. There has long been much debate among scientists about the role of the oxidation state in chemistry [121, 123 - 126]. Some authors point to the universality and fundamentality of the oxidation state. [127, 128, 129]. There is a well-known opinion of Linus Pauling, who said: "If scientific progress continues, the next generation may have a theory of valence that is sufficiently precise and powerful to permit chemistry to be classed along with physics as an exact science" [127, 128]. In [127, 129] it is explicitly stated that the concept of the oxidation state is of fundamental importance in the science of catalysis.

Interest in the state of oxidation in catalysis arose quite a long time ago [11, 130 - 132]. Already in early studies of the influence of the oxidation state on chemical reactions, it was concluded that the activity and selectivity of the catalytic process depend on the oxidation state of the catalyst [131, 132].

Recently, the number of papers investigating the influence of the state of oxidation of a catalyst on the efficiency of catalysis has been rapidly increasing [133 - 138]. The emphasis in these works is on the fact that oxidation states can help predict the reactivity of substances and their chemical activity. In [11] it is noted that "valence chemistry is of fundamental importance in catalysis science," and "the management of oxidation states provides the key to future catalysis research.

Oxidation states play a crucial role in the mechanism of catalysis. The increase in reactivity of reactants depends directly on changes in their oxidation states. We have used the concept of oxidation states to reveal the mechanism of catalysis [139 - 148]. We have used the oxidation states of the participants in a catalytic reaction as quantitative quantities in deriving the laws of catalysis [9, 10, 12, 144, 145, 146, 147, 148].

A hypothetical chemical reaction that takes place without a catalyst can be represented by the following scheme: $A + B \rightarrow AB$. The same reaction in the presence of a catalyst will proceed according to the following simplified scheme [12]: $A + B \rightarrow A(-) + B(+) \rightarrow AB$ (Fig. 1).

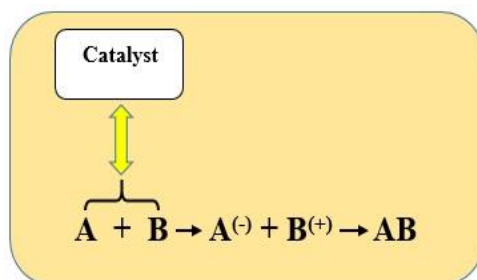


Fig. 1. General scheme of the mechanism of changing the state of oxidation of reagents in catalysis. A, B - reagents; AB - reaction product; $A^{(-)}$ - reagent A in a changed oxidation state; $B^{(+)}$ - reagent B in a changed oxidation state.

In heterogeneous catalysis, the transfer of electric charges is carried out by electrons. A simplified diagram of the mechanism of change in the oxidation state of reactants in heterogeneous catalysis is shown in Fig. 2.

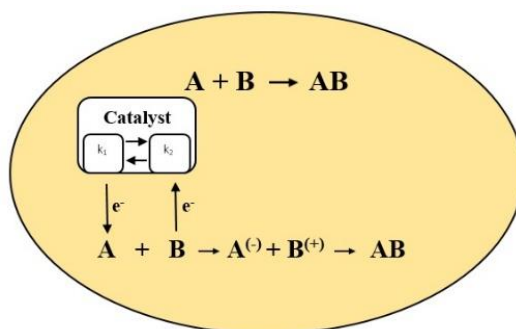


Fig. 2. Simplified diagram of the mechanism of changing the state of oxidation of reagents in heterogeneous catalysis. A, B - reagents; AB - reaction product; $A^{(-)}$ - reagent A in a changed oxidation state; $B^{(+)}$ - reagent B in a changed oxidation state; k_1 - initial oxidation state of the catalyst; k_2 - final oxidation state of the catalyst; e^- - electrons.

In homogeneous catalysis, the transfer of electric charges is carried out by protons. A simplified diagram of the mechanism of change in the state of oxidation of reagents in homogeneous catalysis is shown in Fig. 3.

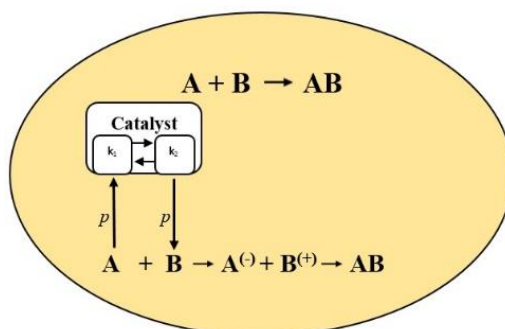


Fig. 3. Simplified diagram of the mechanism of changing the state of oxidation of reagents in homogeneous catalysis. A, B - reagents; AB - reaction product; $A^{(-)}$ - reagent A in a changed oxidation state; $B^{(+)}$ - reagent B in a changed oxidation state; k_1 - initial oxidation state of the catalyst; k_2 - final oxidation state of the catalyst; p - protons.

In field catalysis, electric charge transfer is carried out by electrons. A simplified diagram of the mechanism of change in the state of oxidation of reactants in field catalysis is shown in Fig. 4.

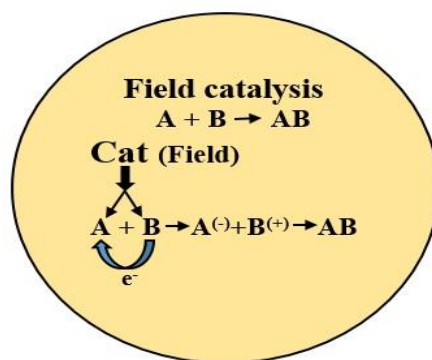


Fig. 4. Schematic diagram of the mechanism of changing the state of oxidation of reagents in field catalysis. A, B - reagents; AB - reaction product; $A^{(-)}$ - reagent A in the changed oxidation state; $B^{(+)}$ - reagent B in the changed oxidation state; e^- - electrons.

The change in the oxidation state of the reactants is directly related to the donor (acceptor) function of the catalyst. The change in the oxidation state of the reagent sets the value of the electric charge transferred to the reagent in the donor half-cycle of the catalysis.

The concept of the oxidation state is a natural complement to the "electron-catalyst" concept and the "proton-catalyst" concept. In the oxidation state concept, the electron and proton have a defining role. In the mechanism of catalysis involving electrons or protons, the transfer of electrons or protons to the reactants leads to a change in the oxidation state of the reactants and an increase in their reactivity.

Despite the great scientific interest in the concept of the oxidation state in catalysis, the current catalysis paradigm does not use oxidation states as quantitative quantities. The new paradigm of catalysis uses oxidation states as quantitative parameters in the laws and equations of catalysis [9, 10, 12, 144 - 148].

Fig. 5 conventionally shows the extension of the application of oxidation states to the field of catalysis in the new catalysis paradigm. Instead of auxiliary conditional quantities that have no physical meaning, the oxidation states act as quantitative quantities in the new catalysis paradigm.

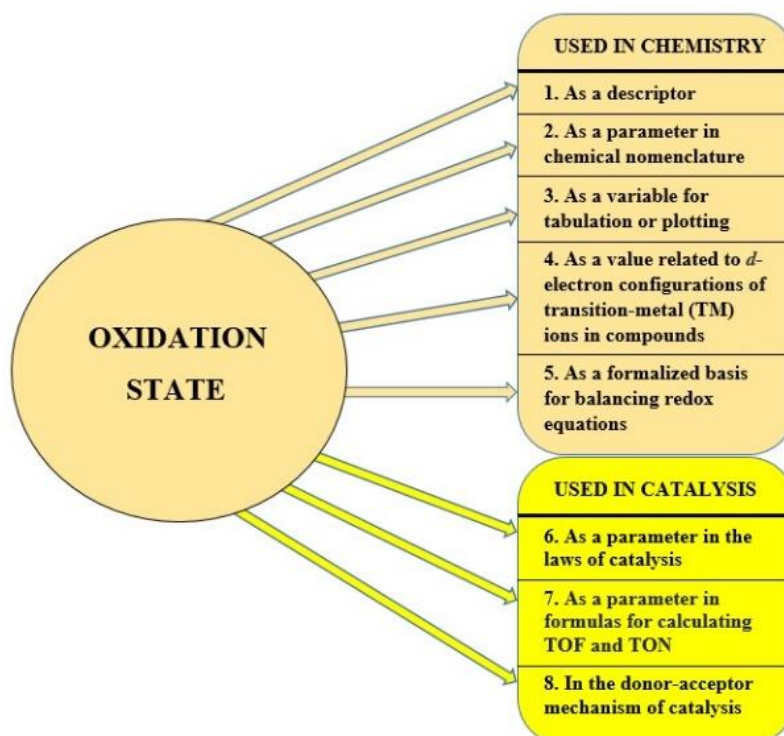


Fig. 5. Expansion of the fields of application of oxidation states to the field of catalysis.

The special role of oxidation states in the mechanism of catalysis has been one of the mysteries of catalysis that has remained unsolved throughout its history. The concept of oxidation states as quantitative quantities has been one of the missing links in the science of catalysis.

In our opinion, such concepts as the oxidation state of the participants in a catalytic reaction, the change in the oxidation state, and the range of change in the oxidation state should become the central concepts of catalysis. Combining the concept of the oxidation state, the electron-catalyst concept, and the proton-catalyst concept within a new paradigm of catalysis is the key to understanding the nature of catalysis and the key to revealing the laws of catalysis.

7. The need for a new paradigm of catalysis

In the current catalysis paradigm, the catalyst and reactants are considered as reaction participants. This paradigm adopts a mechanism that is based on the formation of unstable intermediates between the reactants and the catalyst. The idea of unstable intermediates has become the "central dogma of catalysis. [1]. The current catalysis paradigm adopts a number of restrictions and rules, including the Sabatier restriction for catalysts [19]. The Sabatier principle for the optimal catalyst has been considered one of the most important in catalysis for over 100 years [149].

The discoveries of dynamic catalysis and catalytic resonance [13 - 18] showed that the Sabatier principle is not an absolute rule in catalysis. Under certain conditions, catalysts demonstrate reaction rates several orders of magnitude higher than the Sabatier maximum. These conditions are associated with a change in the electron density of the catalyst [13-18]. The application of the "electron as a catalyst" concept to dynamic catalysis and to catalytic resonance is warranted to explain the role of electrons in this type of catalysis and to develop the theory of catalytic resonance. Experimental proof of overcoming the Sabatier restriction is a challenge to the current catalysis paradigm.

Discoveries of new types of catalysis are a challenge to the modern paradigm of catalysis and to the modern understanding of the nature of catalysis. These are catalysis by electrons, electric field, plasma, microwaves, ultrasound, ionic liquids, catalysis under supercritical conditions, etc. [20, 21, 22].

The greatest challenge to the current catalysis paradigm has been the emergence of three fundamental catalysts in catalysis science. These are two real catalysts (electron and proton) and a third immaterial fundamental catalyst (field). These discoveries call into question the central dogma of catalysis and even affect the terminology of catalysis. For example, the catalyst in the current catalysis paradigm is considered to be a substance. The catalyst field is neither a substance nor a reactant. With the appearance of fundamental catalysts in the science of catalysis, the question of determining the type of interaction of these fundamental physical objects with reagents becomes acute. For fundamental objects, interaction at the level of elementary particles is characteristic. This is a fundamentally different type of interaction. It is fundamentally different from chemical interaction, which leads to the formation of unstable intermediate compounds. And of course we don't have to talk about the formation of intermediate compounds of the electric field with reagents in field catalysis. The emergence of fundamental catalysts in the science of catalysis for the first time in the history of catalysis has exposed and deepened the contradictions of catalysis. These contradictions cannot be resolved by cosmetic changes to the existing paradigm of catalysis. In the nearly 200-year history of catalysis, cosmetic edits have not brought catalysis out of the glut of empiricism and have not led to either a theory of catalytic phenomenon or the laws of catalysis. A simple refinement of the current paradigm of catalysis is not sufficient to resolve the contradictions. It is necessary to formulate

a new paradigm of catalysis. The main goal of creating a new paradigm of catalysis is to reveal the general mechanism of catalytic reactions and to obtain the laws of catalysis.

8. The concept of two fundamental catalysts

Over the past 90 years, the role of the electron in catalysis has been given from a possible participant in the catalytic process to an active participant in the catalytic process. Since 2014, with the advent of the “electron as a catalyst” concept, this fundamental particle has been assigned the role of a catalyst [6, 44]. It is the second catalyst after the proton, which has a fundamental status in science.

Accepting the concepts "electron as a catalyst" and "proton as a catalyst", it is necessary to take into account that the electron and proton are fundamental particles. Among the entire family of real catalysts, only these two particles are fundamental catalysts. The role of a third fundamental catalyst could be claimed by the field within the framework of the concept "electric field as a catalyst". But in this case, it is necessary to take into account that the field is not a real object. In addition, the field can interact with reagents not directly, but indirectly through electrically charged particles - electron and proton. Thus, the whole set of fundamental catalysts is reduced to two fundamental particles: the electron and the proton. The appearance of fundamental catalysts in catalysis allows us to take the next step and move on to the idea of the existence of only two universal catalysts in nature. The electric charges of the fundamental catalysts are the main active factor in increasing the reactivity of chemical substances. The role and place of the field in catalysis have yet to be determined.

We propose to accept a special status for the electron and proton in catalysis. We regard these elementary particles not as additions to the family of known catalysts, but as fundamental and universal catalysts instead of known catalysts. We apply to them the principle: "not together with known catalysts, but instead of them. Such a radical revision of the role of electrons and protons in catalysis instead of cosmetic corrections to the existing catalysis paradigm is justified by their fundamental status and the omnipresence of electrons and protons in nature and in chemical reactions.

9. A new paradigm of catalysis

Combining the concepts of oxidation state, "electron as a catalyst," and "proton as a catalyst" with the concept of two fundamental catalysts allows us to formulate a new paradigm of catalysis.

The new paradigm provides an expanded composition of participants in catalytic reactions. The existing paradigm of catalysis defines the catalyst and reagents as participants in the catalytic process. The new paradigm of catalysis defines the following participants of the catalytic process (Fig. 6):

- catalyst precursor;
- catalyst;
- reagents.

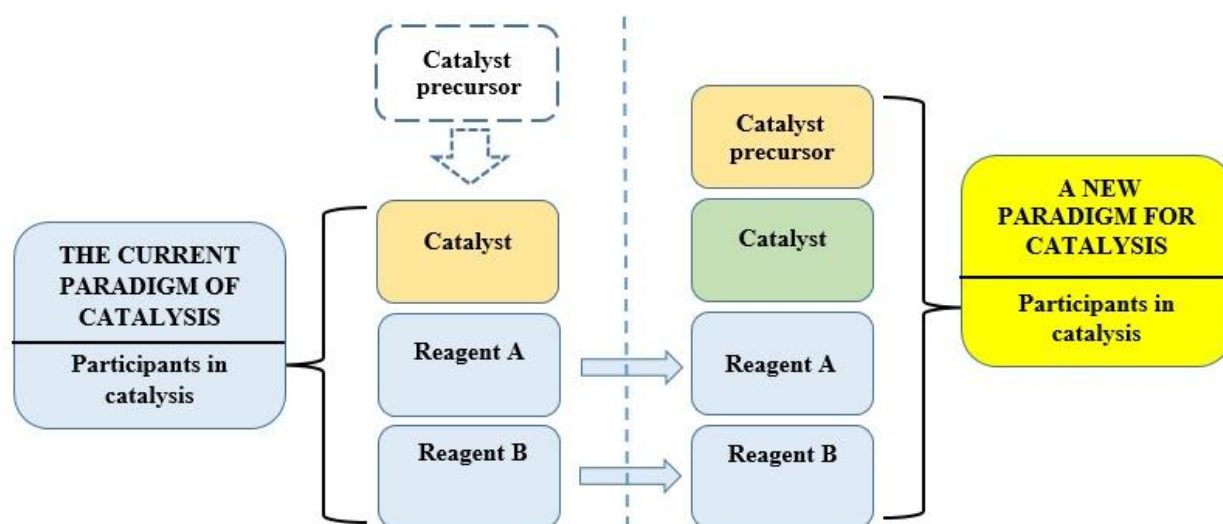


Fig. 6. Participants in the catalytic reaction in the current paradigm and in the new paradigm of catalysis.

The new paradigm of catalysis is built on the idea of the existence of two universal catalysts in nature: the electron and the proton. The main function of catalysts is to increase the reactivity of reagents. This function is realized by changing the oxidation state of the reactants. The new paradigm of catalysis was formed as a natural development and unification of the concepts "electron as a catalyst", "proton as a catalyst", "oxidation state concept" and the concept of two fundamental catalysts.

In the new paradigm of catalysis with the acceptance of the concept of two fundamental catalysts, there is a need to clarify the terminology of catalysis. For example, it is necessary to redefine those substances that were traditionally classified as catalysts. In the new paradigm of catalysis, they act as electron or proton carriers and mediate the donor-acceptor mechanism of catalysis. We will use the term "catalyst precursor" for them at this stage until a more appropriate definition becomes available.

Figure 7 shows a comparison table listing the main features of the old catalysis paradigm and the new catalysis paradigm.

	In the new paradigm of catalysis	In the current paradigm of catalysis
Catalysts	Two fundamental catalysts: the electron and the proton.	Many substances: electrons, protons, transition metals, acids, bases, enzymes, nanoparticles, etc..
Catalysis participants	Catalyst, precursor, reagents	Catalyst, reagents
Catalyst function	Change of oxidation degree of reagents, formation of radicals	Formation of unstable intermediate compounds
Catalyst precursors	Fields of various nature and substances capable of receiving and transmitting electrons or protons.	substance to be activated for use as a catalyst
Interaction of the catalyst with the reagents	Donor-acceptor with a change in the oxidation state of the reagents	Chemical, with the formation of unstable intermediate compounds
Interaction of the precursor with reagents	Donor-acceptor with a change in the oxidation state of the active sites	The precursor is not involved in the catalytic reaction
Mechanism of catalysis	A relay donor-acceptor mechanism.	The Langmuir–Hinshelwood mechanism. The Eley–Rideal mechanism. The Mars–Van Krevelen mechanism. Exclusive mechanisms in different catalytic reactions.

Fig. 7. Comparative table of the main features of the existing and new paradigm of catalysis.

In the new paradigm of catalysis, those substances which have been considered as catalysts so far have taken the place of precursors of catalysts. In catalysis, they are assigned the role of intermediaries in the transfer of electrons and protons. The immaterial (field) catalyst also belongs to the catalyst precursors. A field of various nature plays the role of an electron generator in the substance of reagents in catalysis. In the mechanism of catalysis, the fundamental interaction of the precursor and catalysts with reagents involving catalyst-electrons and catalyst-protons is realized. Electrons and protons perform the function of changing the state of oxidation of the reactants

10. the relay donor-acceptor mechanism as a universal mechanism of catalysis.

It will be possible to get rid of the glut of empiricism in catalysis if the mechanisms of action of catalysts are discovered and the laws of catalysis are discovered. The problem of the mechanism of action of catalysts and the problem of the laws of catalysis are interrelated. The primary problem is the problem of determining the mechanism of action of catalysts. The discovery of the mechanism of catalysis opens up the possibility of discovering the laws of catalysis. Within the new paradigm of catalysis, there is an opportunity to solve both of these problems.

Let us consider a model of the mechanism of catalysis in which all participants are involved: the fundamental catalyst, the precursor, and the reactants. The hypothetical reaction $A + B \rightarrow AB$ with the catalyst (electron, proton) in the presence of the precursor can be represented by the following simplified scheme: $A + B \rightarrow A^{(-)} + B^{(+)} \rightarrow AB$. The mechanism of reaction catalyzed by electron or proton is shown graphically in Fig. 8.

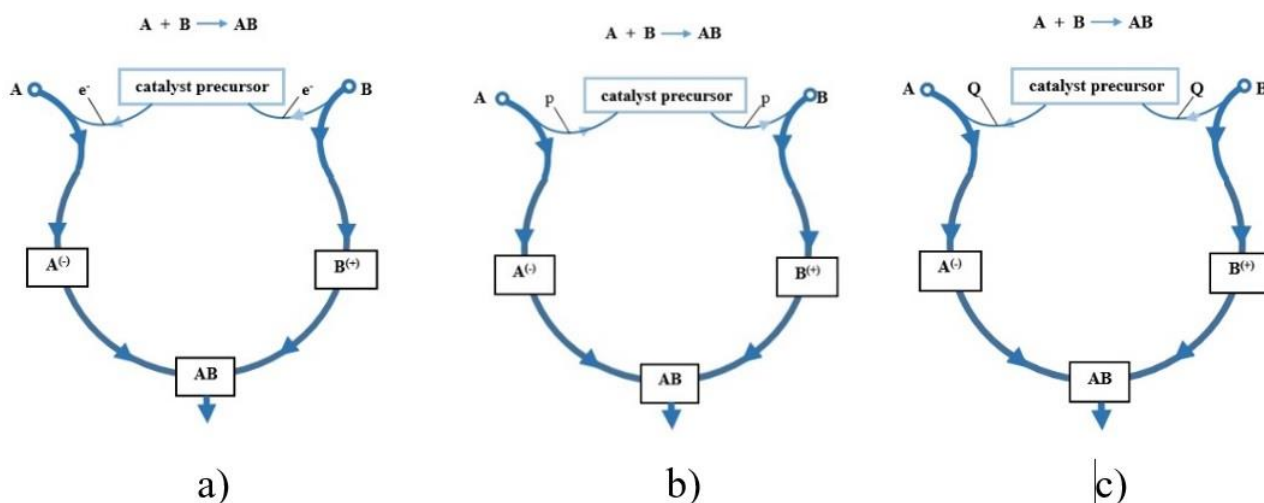


Fig. 8. Schematic of the reaction mechanism, catalyzed by electron or proton. A, B - reagents; AB - reaction product; $A^{(-)}$ - reagent A in changed oxidation state; $B^{(+)}$ - reagent B in changed oxidation state; e^{-} - electrons; p - protons; Q - electric charge; a) - reaction mechanism in which electron is the catalyst; b) - reaction mechanism in which proton is the catalyst; c) - general scheme of catalysis mechanism.

Fig. 8-a shows a diagram of the mechanism of the reaction catalyzed by the electron. FIG. 8-b shows a diagram of the mechanism of the reaction catalyzed by a proton. FIG. 8-c shows a general scheme of the reaction mechanism. It is clear from the general scheme that the catalysts perform the function of transferring electric charges in the catalytic reaction. This leads to a change in the state of oxidation of the reactants and, consequently, an increase in the reactivity of the reactants.

Thus, the general mechanism for catalytic reactions is a mechanism based on the transfer of electric charges by electrons and protons and on the change in the state of oxidation of the reactants with their participation. This is the relay donor-acceptor mechanism of catalysis. It is implemented according to a single-type scheme and is a universal mechanism of catalysis with the participation of both electrons and protons.

Let us consider the scheme of the relay donor-acceptor mechanism by the example of heterogeneous catalysis. The mechanism scheme has peculiarities depending on the initial charge state of the active precursor site. If the charge state of the active site is electron-deficient, the precursor implements an acceptor function. The active site accepts electrons from reagent B_i . After that, the donor function of the active site is realized. The active site transfers electrons to reagent A_i . The catalyst precursor completes its acceptor-donor cycle in the elementary catalytic reaction and ensures the preparation of reactants A_i and B_i for the chemical reaction. Similarly, $(i-1)$ -th and $(i+1)$ -th elementary reactions take place. The chemical reaction takes place between the charge-conjugated reagents in the changed oxidation state, $A_i^{(-)}$ and $B_i^{(+)}$. A simplified diagram of the reaction mechanism is shown in Fig. 9.

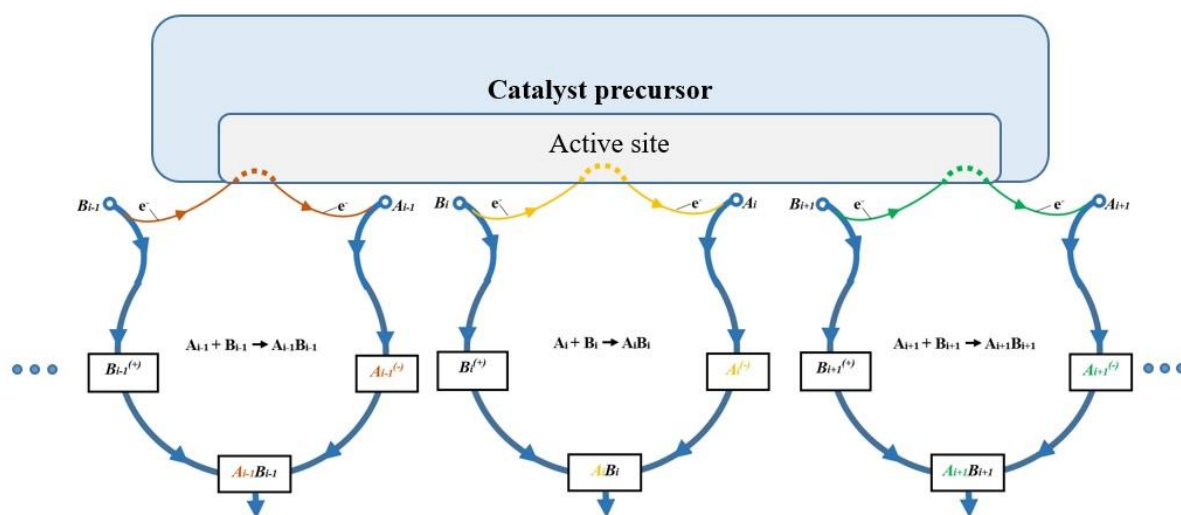


Fig. 9. Diagram of the relay donor-acceptor mechanism of heterogeneous catalysis. A_i , B_i - reagents participating in the i -th elementary reaction; A_{i-1} , B_{i-1} - reagents participating in the $(i-1)$ -th elementary reaction; A_{i+1} , B_{i+1} - reagents participating in the $(i+1)$ -th elementary reaction; $A_i B_i$ - product of the i -th elementary reaction; $A_{i-1} B_{i-1}$ - product of the $(i-1)$ -th elementary reaction; $A_{i+1} B_{i+1}$ - product of the $(i+1)$ -th elementary reaction; $A^{(-)}$ - reagent A in a changed oxidation state; $B^{(+)}$ - reagent B in a changed oxidation state; e^- - electrons; $(A_i + B_i \rightarrow A_i B_i)$ i - elementary reaction; $(A_{i-1} + B_{i-1} \rightarrow A_{i-1} B_{i-1})$ $(i-1)$ -elementary reaction; $(A_{i+1} + B_{i+1} \rightarrow A_{i+1} B_{i+1})$ $(i+1)$ -elementary reaction.

As we can see, the catalyst precursor acts as an intermediary in the transfer of electrical charges from one reactant to another. The omnipresence of electrons and their uniformity allows the charge state of a participant in catalysis to be changed by the transfer of any free electron. The path of the electron in an elementary catalytic reaction ends in the reaction product, where the charge-conjugated reactants form a neutral molecule. The next $(i+1)$ -th elementary reaction will involve another electron obtained by the precursor from another reactant. Its path will end in the product of the $(i+1)$ -th elementary reaction, where the charge-conjugate reagents form the next neutral molecule.

If the charge state of the active site is electron-abundant, the process begins with the donor function of the precursor. The active site transfers an electron to the reagent A_i . Then the acceptor function of the active site is realized. The active site accepts an electron from reagent B_i . The catalyst

precursor completes its donor-acceptor cycle in the elementary catalytic reaction and provides the preparation of reactants B_i and A_i for the chemical reaction. The chemical reaction takes place between the charge-conjugated reactants in an altered oxidation state of $A_i^{(-)}$ and $B_i^{(+)}$. The electron obtained by the precursor from reactant B_i will take part in one of the following elementary catalytic reactions as a donor electron. A simplified scheme of the mechanism is shown in Fig. 10.

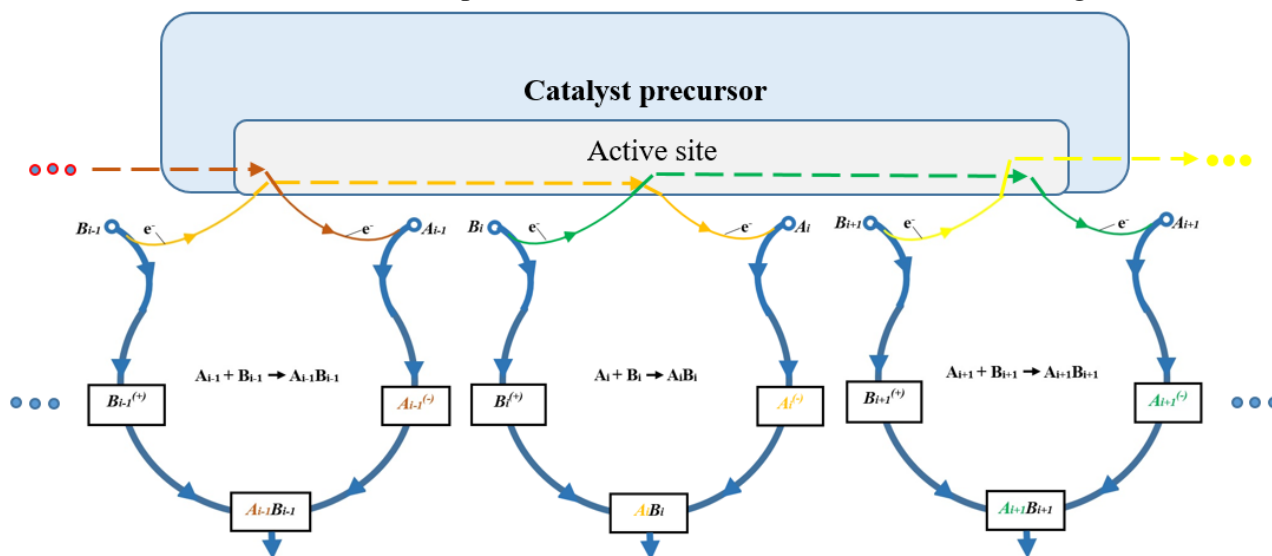


Fig. 10. Diagram of the relay donor-acceptor mechanism of heterogeneous catalysis. A_i , B_i - reagents participating in the i -th elementary reaction; A_{i-1} , B_{i-1} - reagents participating in the $(i-1)$ -th elementary reaction; A_{i+1} , B_{i+1} - reagents participating in the $(i+1)$ -th elementary reaction; A_iB_i - product of the i -th elementary reaction; $A_{i-1}B_{i-1}$ - product of the $(i-1)$ -th elementary reaction; $A_{i+1}B_{i+1}$ - product of the $(i+1)$ -th elementary reaction; $A^{(-)}$ - reagent A in a changed oxidation state; $B^{(+)}$ - reagent B in a changed oxidation state; e^- - electrons; $(A_i + B_i \rightarrow A_iB_i)$ i - elementary reaction; $(A_{i-1} + B_{i-1} \rightarrow A_{i-1}B_{i-1})$ $(i-1)$ -th elementary reaction; $(A_{i+1} + B_{i+1} \rightarrow A_{i+1}B_{i+1})$ $(i+1)$ -th elementary reaction.

The source of electrons (donor) is one of the reactants. The precursor mediates the transfer of electrons to the second reagent and acts as an electron donor for the second reagent. The electrons obtained by the precursor are relayed electrons to the next reactant and will be included in the product formed by other reaction participants in the next $(i+1)$ -stage of catalysis. In the relayed donor-acceptor mechanism of catalysis, the donor-acceptor cycle of the catalyst precursor is a preparatory stage. This stage precedes the chemical reaction of the reactants. This stage of catalysis completes the preparation of the reactants for the chemical reaction. The reactants change their oxidation state. Changing the oxidation state of the reactants leads to an increase in their reactivity. The second stage of the relay donor-acceptor mechanism of catalysis is the chemical reaction of the charge-conjugated reagents $A_i^{(-)}$ and $B_i^{(+)}$. At the second stage, the donor-acceptor cycle of reagents is realized. Reagent $A_i^{(-)}$, which received electrons from the precursor, acts as an electron donor with respect to the second reagent $B_i^{(+)}$. Accordingly, reagent $B_i^{(+)}$ acts as an electron acceptor with respect to reagent $A_i^{(-)}$. The donor reagent $A_i^{(-)}$ transfers an electron to the acceptor reagent $B_i^{(+)}$. As a result, a neutral molecule A_iB_i , a product of the elementary catalytic reaction, is formed

11. Laws of catalysis

Within the new paradigm of catalysis, we set out to obtain the laws of catalysis as a function of the characteristics of all participants in the catalytic reaction: catalyst, catalyst precursor, and reagents. The laws of catalysis were obtained in [139 - 143]. The general laws and equations of catalysis are shown in Fig. 11.

$$\begin{aligned}
 1) \quad v_{cat} &= \frac{Q_{\Sigma}}{F \cdot t \cdot m_2 \cdot |q_1 - q_2|} \\
 2) \quad n_{cat} &= \frac{Q_{\Sigma}}{F \cdot m_2 \cdot |q_1 - q_2|} \\
 3) \quad N_{kat}^{red} + N_{kat}^{ox} &= m_1 \cdot N_1^{red} + m_2 \cdot N_2^{ox} \\
 4) \quad \frac{2 \cdot E_{cat}}{E_i} &= m_1 \cdot N_1^{red} + m_2 \cdot N_2^{ox} \\
 5) \quad RON \cdot n_a &= n \cdot N_A \cdot \sigma
 \end{aligned}$$

Fig. 11: General laws and equations of catalysis. 1). The universal law of the rate of catalysis [148]. 2). General formula for calculation of Quantity (mol) of the reaction product [148]. 3). Catalytic balance equation [145-148]. 4). Catalytic balance equation for field catalysis [9, 10]. 5). The law of conservation in catalysis [145-148].

Fig. 12. shows the rate laws for heterogeneous [145, 148], homogeneous [147, 148], field [9, 10] and combined catalysis [148] and formulas for calculating Quantity (mol) of the reaction product [145 - 148].

$$\begin{aligned}
 v_{He} &= \frac{e \cdot n_a \cdot |k_1 - k_2|}{F \cdot (\tau_D + \tau_A) \cdot m_2 \cdot |q_1 - q_2|} \\
 v_{Ho} &= \frac{e \cdot n_a}{F \cdot (\tau_D + \tau_A) \cdot m_2 \cdot |q_1 - q_2|} \\
 v_{Fcat} &= \frac{e \cdot f_e \cdot E_{cat}}{F \cdot m_2 \cdot |q_1 - q_2| \cdot E_i} \\
 v_{Comb} &= \frac{e \cdot n_a \cdot (|k_1 - k_2| + \dots + |r_1 - r_2|)}{F \cdot (\tau_D + \tau_A) \cdot m_2 \cdot |q_1 - q_2|}
 \end{aligned}$$

a)

$$\begin{aligned}
 n_{He} &= \frac{e \cdot n_a \cdot t \cdot |k_1 - k_2|}{F \cdot (\tau_D + \tau_A) \cdot m_2 \cdot |q_1 - q_2|} \\
 n_{Ho} &= \frac{e \cdot n_a \cdot t}{F \cdot (\tau_D + \tau_A) \cdot m_2 \cdot |q_1 - q_2|} \\
 n_{Fcat} &= \frac{t \cdot e \cdot f_e \cdot E_{cat}}{F \cdot m_2 \cdot |q_1 - q_2| \cdot E_i} \\
 n_{Comb} &= \frac{e \cdot n_a \cdot (|k_1 - k_2| + \dots + |r_1 - r_2|) \cdot t}{F \cdot (\tau_D + \tau_A) \cdot m_2 \cdot |q_1 - q_2|}
 \end{aligned}$$

b)

Fig. 12: Laws of catalysis; a) rate laws for heterogeneous, homogeneous, field and combined catalysis; b) formulas to calculate the Quantity (mol) of the reaction product.

In the new paradigm of catalysis, the laws of catalysis rate are defined as the amount of catalytic reaction product per unit time (mol/s). The laws of catalysis are derived as applied to the elementary catalytic reaction and follow directly from the relay donor-acceptor mechanism of catalysis. The laws of catalysis are not presented as functions of the concentration of the reactants, but are presented as functions of the substance characteristics of all participants in the reaction. The laws of catalysis follow directly from the mechanism model of the corresponding type of catalysis.

In essence, each law of catalysis is a mathematical equivalent of the mechanism of the corresponding type of catalysis. The characteristics of the reaction participants are included in the catalysis laws as parameters.

FIG. 13 shows a comparative table of ways to calculate Turnover frequency TOF in different types of catalysis.

	In the current paradigm of catalysis	In the new paradigm of catalysis
General formula for calculating the TOF	$TOF = \frac{N}{t \cdot n_a}$ [150, 151]	$TOF_{cat} = \frac{Q_{\Sigma}}{e \cdot n_a \cdot t \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]
Turnover frequency TOF in heterogeneous catalysis	$TOF = \frac{N}{t \cdot n_a}$ [150, 151]	$TOF_{He} = \frac{ \dot{k}_1 - \dot{k}_2 }{(\tau_D + \tau_A) \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]
Turnover frequency TOF in homogeneous catalysis	$TOF = \frac{N}{t \cdot n_a}$ [150, 151]	$TOF_{Ho} = \frac{1}{(\tau_D + \tau_A) \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]
Turnover frequency TOF in field catalysis	$TOF = \frac{N}{t \cdot n_a}$ [150, 151]	$TOF_{Fcat} = \frac{f_e \cdot E_{cat}}{m_2 \cdot q_1 - q_2 \cdot E_i}$ [9, 148]
Turnover frequency TOF in combined catalysis	$TOF = \frac{N}{t \cdot n_a}$ [150, 151]	$TOF_{Comb} = \frac{ \dot{k}_1 - \dot{k}_2 + \dots + r_1 + r_2 }{(\tau_D + \tau_A) \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]

FIG. 13: Comparative table of methods of calculating TOF in different types of catalysis.

FIG. 14 is a comparative table of ways to calculate TON in different types of catalysis.

	In the current paradigm of catalysis	In the new paradigm of catalysis
General formula for calculating the TON	$TON = \frac{N}{n_a}$ [150, 151]	$TON_{cat} = \frac{Q_{\Sigma}}{e \cdot n_a \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]
Turnover number TON in heterogeneous catalysis	$TON = \frac{N}{n_a}$ [150, 151]	$TON_{He} = \frac{ \dot{k}_1 - \dot{k}_2 \cdot t}{(\tau_D + \tau_A) \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]
Turnover number TON in homogeneous catalysis	$TON = \frac{N}{n_a}$ [150, 151]	$TON_{Ho} = \frac{t}{(\tau_D + \tau_A) \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]
Turnover number TON in field catalysis	$TON = \frac{N}{n_a}$ [150, 151]	$TON_{Fcat} = \frac{t \cdot f_e \cdot E_{cat}}{m_2 \cdot q_1 - q_2 \cdot E_i}$ [9, 148]
Turnover number TON in combined catalysis	$TON = \frac{N}{n_a}$ [150, 151]	$TON_{Comb} = \frac{(\dot{k}_1 - \dot{k}_2 + \dots + r_1 + r_2) \cdot t}{(\tau_D + \tau_A) \cdot m_2 \cdot q_1 - q_2 }$ [144, 148]

FIG. 14: Comparative table of methods of calculating TON in different types of catalyst.

Fig. 15 shows the integral characteristics of the catalyst precursor and the reduction number of the catalyst. They are Redox frequency ROF and Redox number RON [142]. ROF and RON values are related to TOF and TON by means of Horiuti numbers [152].

	In the current paradigm of catalysis	In the new paradigm of catalysis
Redox frequency ROF	-	$ROF = \frac{1}{\tau_D + \tau_A}$ [142, 145]
Redox number RON	-	$RON = \frac{t}{\tau_D + \tau_A}$ [142, 145]
Redox frequency ROF in field catalysis	-	$ROF_{Fcat} = f_e$ [9]
Redox number RON in field catalysis	-	$RON_{Fcat} = t \cdot f_e$ [9]
Reduction number of the catalysis	-	$\sigma = \frac{ROF}{TOF} = \frac{RON}{TON} \sigma = \frac{m_1 \cdot \tau_1 - \tau_2 }{ \tilde{k}_1 - \tilde{k}_2 } = \frac{m_2 \cdot q_1 - q_2 }{ \tilde{k}_1 - \tilde{k}_2 }$ [142, 145]

FIG. 15: Integral characteristics of the catalyst precursor and catalyst reduction number.

The reduction number of the catalyst indicates how many times the oxidation state change cycle of the precursor must be repeated before one particle of the final product is formed.

12. Reduction of the universal law of catalysis to the partial laws of catalysis and to Faraday's law of electrolysis

From the universal law of catalysis, as private results, follow the laws of heterogeneous, homogeneous, field catalysis, combined catalysis, and Faraday's law of electrolysis (Fig. 16) [148]. This is a confirmation of the unified nature of all types of catalysis. The reduction of the universal law of catalysis to Faraday's law of electrolysis is evidence that electrolysis belongs to a class of catalytic reactions.

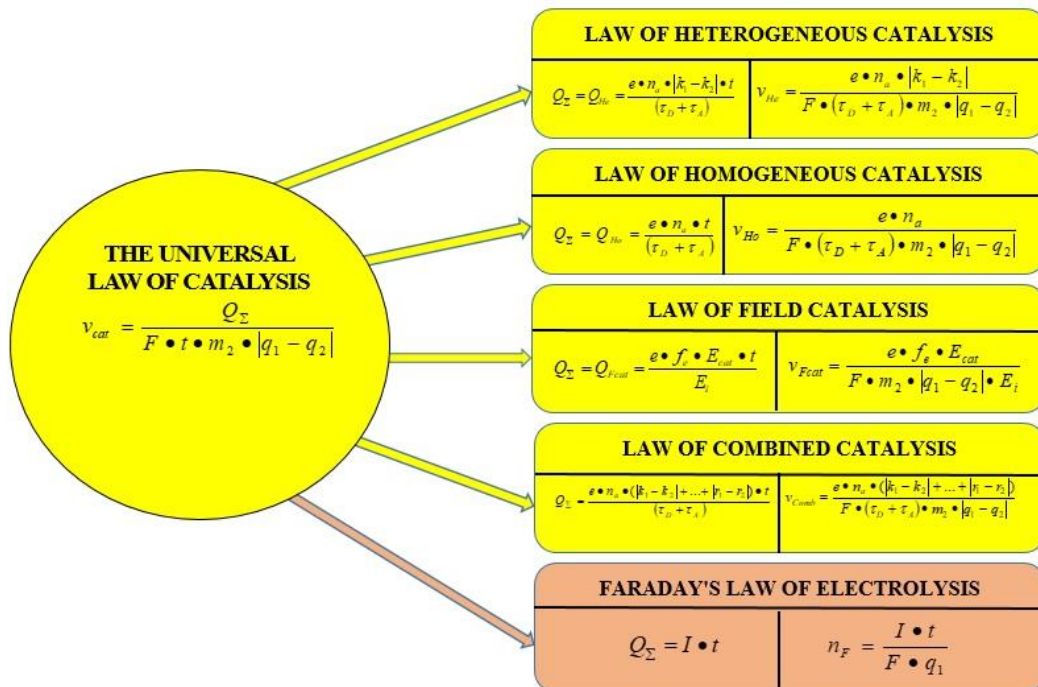


Fig. 16. Reduction of the universal law of catalysis to private laws of catalysis and to Faraday's law of electrolysis

13. What characteristics are represented by the catalyst, precursor, and reactants in the laws of catalysis?

The laws of catalysis are quantitative mathematical models of the chemical-physical processes that are realized in a catalytic reaction. In the laws of catalysis (Fig. 11), (Fig. 12) there are values of chemical and physical nature. All participants of catalytic reaction (catalyst precursor, catalyst, reagents) are represented in the laws of catalysis by their characteristics. The fundamental catalysts are represented by the fundamental physical constants, Faraday's constant F ($F = 96485.3321233100184 \text{ C/mol}$) and the electron charge e ($e = 1.602\ 176\ 634 \times 10^{-19} \text{ C}$). These are electrical quantities. Faraday's constant is the electrical charge of one mole of electrons or one mole of protons. The presence of Faraday's constant in the laws and formulas of chemistry is not limited to Faraday's law of electrolysis, the Nernst equation, and Goldman's equation. Fig. 17 conventionally shows the extension of the application of Faraday's constant beyond the known laws and equations of chemistry and extending it to the field of catalysis.

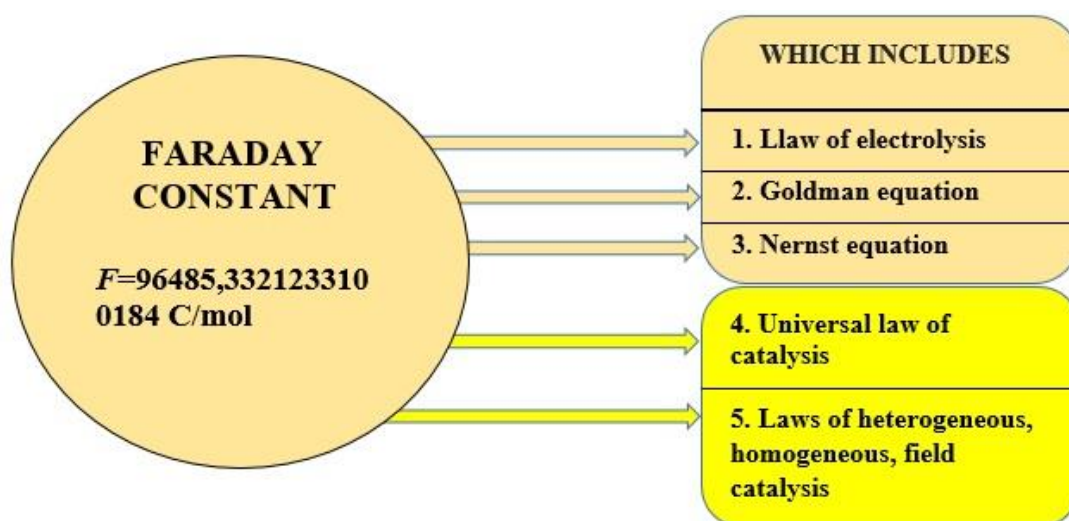


Fig. 17: Extension of the application of the Faraday constant to the field of catalysis.

Characteristics of the precursor-substance are: number of active sites n_a , oxidation states k_1 , k_2 of the active precursor site; duration of the donor τ_D and acceptor τ_A stages. The characteristics of the precursor-field are: field energy E_{cat} , frequency f_e .

Characteristics of reagents are: states of oxidation of reagent A (z_1, z_2), states of oxidation of reagent B (q_1, q_2); number of atoms m_1 of reagent A in the molecule of the final product; number of atoms m_2 of reagent B in the molecule of the final product and ionization energy E_i . In Fig. 18 the characteristics of all participants of catalytic reaction are presented. These characteristics are included as parameters in the laws and equations of catalysis.

	Name	Characteristics	Designation
Catalyst	Electron	Electric charge of the electron e , charge of one mole of electrons F (Faraday's constant)	e, F
Catalyst	Proton	Electric charge of the proton e , charge of one mole of protons F (Faraday's constant)	e, F
Catalyst precursor	Substance	Number of active sites n_a , degrees of oxidation of the active precursor site k_1, k_2, r_1, r_2 ; τ_D - electron (proton) transfer time to the reagent A, τ_A - time of obtaining an electron (proton) from the reagent B.	$n_a, k_1, k_2, r_1, r_2, \tau_D, \tau_A$
Catalyst precursor	Field	Field energy E_{cat} , frequency f_e	E_{cat}, f_e
Reagents	Reagent A, Reagent B	Reagent A oxidation state z_1, z_2 ; reagent B oxidation state q_1, q_2 ; m_1 - number of atoms of reagent A in the product; m_2 - number of atoms of reagent B in the product, ionization energy E_i	$z_1, z_2, q_1, q_2, m_1, m_2, E_i$

FIG. 18 Characteristics of catalytic reaction participants in the laws of catalysis.

In Fig. 19 the example of heterogeneous catalysis shows which characteristics of the catalyst precursor, catalyst and reagents are the parameters in the law of speed of heterogeneous catalysis.

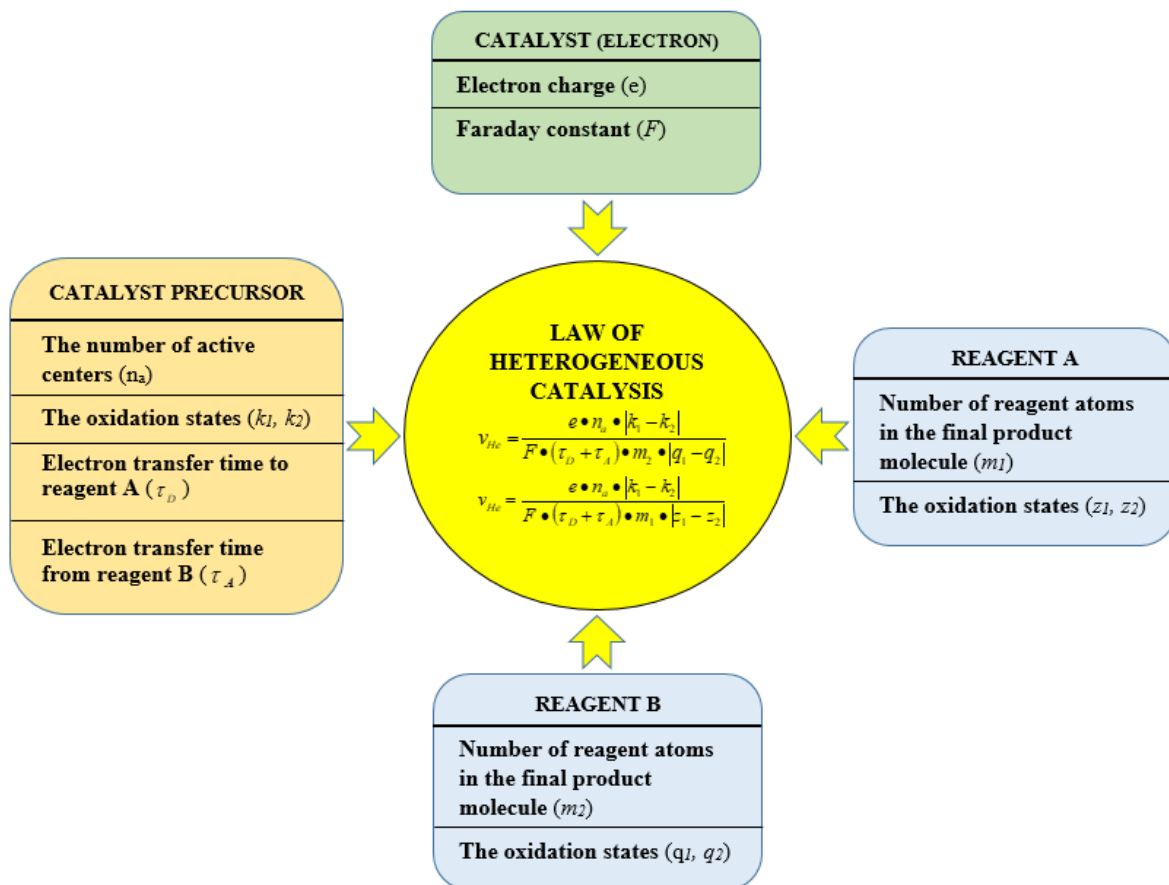


FIG. 19: Characteristics of catalytic reaction participants in the rate law of heterogeneous catalysis.

FIG. 20 shows in the example of field catalysis what characteristics of the catalyst precursor, catalyst and reagents are the parameters in the field catalysis rate law.

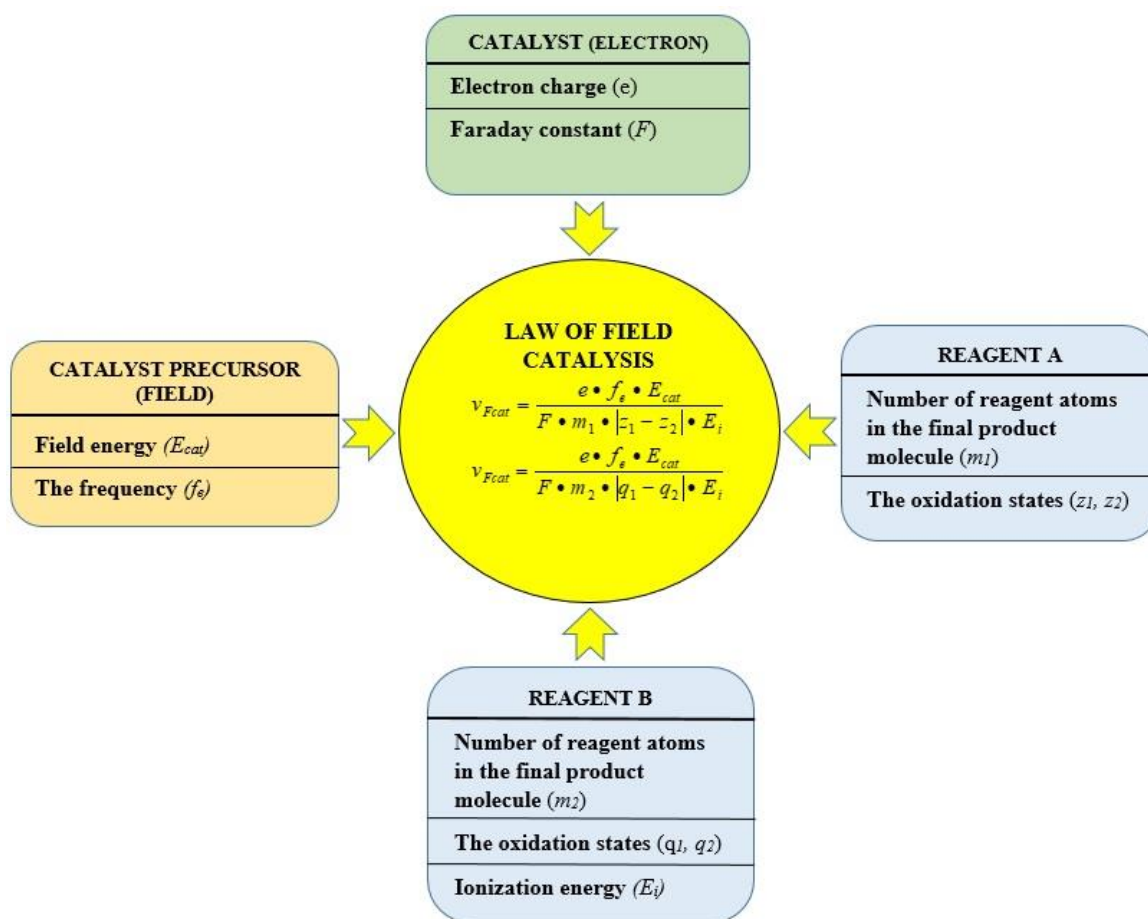


Fig. 20. Characteristics of the catalytic reaction participants in the field catalysis rate law.

14. Catalysis as a fundamental phenomenon at the interface between sciences and disciplines.

Catalysis is a fundamental phenomenon and has an interdisciplinary character [12]. Catalysis occupies a place at the interface of two sciences - chemistry and physics. The laws of catalysis are the confirmation of the interdisciplinary character of catalysis and its fundamental status. The parameters in the laws of catalysis are chemical and physical quantities. In [12], it was shown that in the laws of catalysis, chemical quantities dominate over physical quantities. The laws of catalysis have much in common with the fundamental physical laws. The phenomenon of catalysis, like the fundamental physical phenomena, is characterized by a certain type of interaction. In catalysis, the donor-acceptor interaction between the participants of the process is realized. Like the fundamental physical laws, the laws of catalysis have an interaction constant. The interaction constant in the laws of catalysis is the Faraday constant. Fundamental physical laws are quantitative mathematical models of physical phenomena. They are represented by a combination of physical quantities. The laws of catalysis are also quantitative mathematical models of chemical-physical phenomena. The peculiarity of the laws of catalysis is their interdisciplinary nature. For this reason, the laws of catalysis are represented by a combination of chemical and physical quantities [12]. As far as we know, the laws of catalysis are the first representatives of interdisciplinary laws represented not by empirical equations, but by quantitative mathematical models.

Fig. 21 shows a comparative table showing common features between the universal law of catalysis and the fundamental laws of Nature. Newton's law of gravity, Coulomb's law, Faraday's law

of electrolysis, Ohm's law and the law of catalysis are taken for comparison. The universal law of catalysis complements the family of fundamental laws of Nature.

	Law of gravity	Coulomb's law	Faraday Laws of electrolysis	Ohm's Law	The universal law of catalysis
Type of interaction	Gravitational	Electro-magnetic	Electro-magnetic	Electro-magnetic	Donor-acceptor
Conservation law	Conservation of energy law	Law of conservation of electrical charge	Law of conservation of electrical charge	Conservation of energy law	Law of conservation of electrical charge
Characteristic	Force (F)	Force (F)	Quantity of the reaction product (nF)	Electric current (I)	Catalysis reaction speed (v)
Acting factor	Gravitational charge	Electrical charge	Electric current (I)	Electric current (I)	Electrical charge (Q_z)
Law Formula	$F = G \frac{m_1 \cdot m_2}{r^2}$	$F = k \frac{q_1 \cdot q_2}{r^2}$	$n_p = \frac{I \cdot t}{F \cdot z_1}$	$I = \frac{U}{R}$	$v_{cat} = \frac{Q_z}{F \cdot t \cdot m_2 \cdot q_1 - q_2 }$ $v = \frac{e \cdot n_p \cdot IOF}{F}$
Interaction constant	G	k	F (Faraday constant)	R	F (Faraday constant)
Interaction constant formula	-	$k = \frac{1}{4\pi\epsilon_0}$	$F = e \cdot N_A$	$R = \frac{\rho \cdot l}{S}$	$F = e \cdot N_A$
Theory	Gravitation theory	Electro magnetic theory	Electrolysis theory	Electric circuit theory	Donor-acceptor theory of catalysis

Fig. 21. The universal law of catalysis complements the family of fundamental physical laws.

15. Conclusion

The concept of "electron as a catalyst" becomes an independent area of research in catalysis [153 - 157]. The concept of "electron as a catalyst," the concept of two fundamental catalysts, and the concept of the oxidation degree were the main missing links in the science of catalysis. Combining them allowed a new paradigm of catalysis to be formulated. The new paradigm of catalysis made it possible to reveal the universal donor-acceptor mechanism of catalytic reactions and to solve the main problem of catalysis: to obtain a single universal law of catalysis. From the universal law of catalysis, the laws of heterogeneous, homogeneous, field catalysis, and Faraday's law of electrolysis follow as particular results. The parameters in the laws of catalysis are the chemical and physical characteristics of all participants in the reaction. In the new paradigm of catalysis, the number of reaction participants is expanded. The participants in the catalytic reaction are the precursor, the fundamental catalyst, and the reactants. The characteristics of the electron and proton are fundamental physical constants. The characteristics of the precursor and the characteristics of the reactants are oxidation states. The oxidation states are applied in the laws of catalysis for a new purpose as quantitative quantities. The mechanism of action of the fundamental catalysts is to change the charge state of the reactants. A consequence of the change in the charge state of the reactants is a change in their reactivity.

In the new catalyst paradigm, a catalyst precursor is a substance or field that is a supplier (generator) of electrons or protons. A catalyst precursor mediates the transfer of catalysts between reactants. Precursors in heterogeneous catalysis are substances that mediate the transfer of electrons between reactants. Precursors in homogeneous catalysis are substances that donate protons. Precursors in organocatalysis are organic substances electron donors. Precursors in field catalysis are electron generators in the substance reagents. The precursors in field catalysis are electric field (electrostatic catalysis), electric current (electrocatalysis), light (photocatalysis, laser catalysis),

ultrasound (cavitation catalysis), ionized radiation (radiation catalysis), plasma (plasma catalysis), microwave radiation (microwave catalysis), etc.

The new paradigm of catalysis logically leads to the conclusion that all chemical reactions are catalytic. They take place with the participation of two types of catalysts - electrons or protons. The two fundamental particles electron and proton are the two universal catalysts for all chemical reactions. In those reactions that were not traditionally classified as catalytic, the role of catalyst supplier and catalyst precursor is played by one of the reactants. Nature invented catalysts for chemical and biochemical reactions. Since "nature is simple and does not luxuriate in superfluous causes of things," it may well have chosen only two fundamental objects as universal catalysts: the electron and the proton.

16. Conclusions

1. A new paradigm of catalysis, based on the idea of the existence in nature of two fundamental catalysts that can increase the reactivity of chemical substances, has been proposed.

2. The new paradigm of catalysis is developed as a natural extension of the advanced concepts in catalysis such as "electron as a catalyst", "proton as a catalyst", "oxidation state concept" and the concept of two fundamental catalysts.

3. The catalysts in all types of catalysis are fundamental objects of microcosm - elementary particles: electron and proton. Two charge-symmetric catalysts are enough to give a consistent explanation of the catalytic phenomenon.

4. The new paradigm of catalysis defines an expanded composition of participants in catalytic reactions. The participants of catalytic reactions are: catalyst, catalyst precursor, and reactants. The composition of reaction participants includes an electron or proton in the role of universal catalysts.

5. In the new paradigm of catalysis, the catalyst precursors include a substance or a field. Numerous catalyst precursor substances act as intermediaries in the transfer of electrons and protons. The field acts as a generator of catalysts in the reagent substance.

6. The single mechanism of catalytic reactions in various types of catalysis is a mechanism based on the transfer of electrical charges by electrons and protons and on the change in the state of oxidation of the reactants with their participation.

7. Based on the concepts of "electron as a catalyst", "proton as a catalyst", the concept of oxidation state and the concept of two fundamental catalysts, a model of the relay donor-acceptor mechanism as a universal mechanism of catalysis is proposed.

8. The new paradigm of catalysis made it possible to reveal the universal mechanism of catalytic reactions and to solve the main problem of catalysis - to obtain a single universal law of catalysis. From the universal law of catalysis, as particular results, follow the laws of heterogeneous, homogeneous, field catalysis and Faraday's law of electrolysis.

9. The laws of catalysis are represented by mathematical relations in which the parameters are chemical and physical characteristics of all the reaction participants: catalyst, precursor, and reagents. The characteristics of the catalyst are the fundamental physical constants. The characteristics of the precursor and the reactants are the states of oxidation.

10. The electron-catalyst concept, the oxidation state concept, and the concept of two fundamental catalysts were the main missing links in catalytic science. Their absence in the science of catalysis for almost 200 years prevented the mechanism of catalytic reactions and the laws of catalysis from being revealed.

11 The primary function of catalysts is to change the reactivity of reactants. Catalysts accomplish this function by changing the oxidation state of the reactants.

12. All chemical reactions are catalytic and are carried out by a single universal mechanism of catalysis. In those reactions that are not traditionally catalytic, the catalysts are an electron or proton, and the role of a precursor and donor of elementary particles is performed by one of the reactants.

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