THE HISTORY OF CYBERNETICS AND ARTIFICIAL INTELLIGENCE: A VIEW FROM SAINT PETERSBURG

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Abstract

In the article the history of cybernetics and artificial intelligence in the world and, particularly in the USSR is outlined starting from the 1940s-1950s. The rapid development of these areas in the 1960s is described in more detail. Special attention is paid to the results of Leningrad (St. Petersburg) researchers, particularly to the work of Vladimir Yakubovich and his scientific school on machine learning, pattern recognition, adaptive systems, intelligent robots and their importance for the further development of cybernetics and artificial intelligence.

Key words

Artificial Intelligence (AI), Machine Learning, Neural Networks, Convex Optimization

1 Introduction

The history of science is a very important area for the city of St. Petersburg, where not many Russian scientific schools were born. The reports devoted to history make us think not only about the history of science in general, but also about the history of our society, our country and the world. This article is devoted to the development of cybernetics and artificial intelligence (AI) in the world and in the USSR (Russia). The first section is devoted to the early years of cybernetics and artificial intelligence: 1940s-1950s. The heroic time of the 1960s usually called the spring of cybernetics and AI is outlined in the second section. The third section is dedicated to the contributions of V.A. Yakubovich to AI: machine learning, pattern recognition, adaptive systems, and robots. The fourth section is mainly devoted to the contributions of L. Bregman: Bregman's method, Bregman's divergence which became in demand in AI nowadays. The material of the article is based on publications: [Fradkov, 2008; Fradkov, 2014; Gusev and Bondarko, 2020; Fradkov, 2020; Annaswamy and Fradkov, 2021].

2 The early years of cybernetics and artificial intelligence: 1940-1950

Let's start with the birth of the science of cybernetics and artificial intelligence. These two areas, considered different, were actually born, if we trace the origins, from one article by American scientists Warren McCulloch (1898-1969) and Walter Pitts (1923-1969)) "Logical calculus of ideas related to nervous activity", published in 1943 [McCulloch and Pitts, 1943]. In this work for the first time, a formal neuron model was presented, which is now called the McCulloch-Pitts neuron model , Fig.1. It has been shown that by connecting neurons into a network, it is possible to obtain a structure that works in the same way as a Turing machine, i.e. can evaluate computable functions.

Thus, the first artificial neural network was born in this work. Walter Pitts was very young then. He was not twenty years old when this paper was published. In fact, he wasn't even a student yet. Norbert Wiener, who was already creating a laboratory at MIT, noticed him and the authors of this article, and invited them to work there. Pitts began studying at MIT. Thus, the cybernetic line began to develop, although the word "cybernetics" was still known to few people at that time.

Norbert Wiener is considered the founder of cybernetics, which was born in his famous book "Cybernetics or Control and Communication in an animal and a machine", published in 1948 simultaneously in the USA and in Europe [Wiener, 1948]. The ideas presented in the book were further developed and disseminated at a series of conferences in 1946-1953, (Macy's Conferences) sponsored by the Josiah Macy, Jr. Foundation, the conferences were aimed at uniting an interdisciplinary com-

[th]

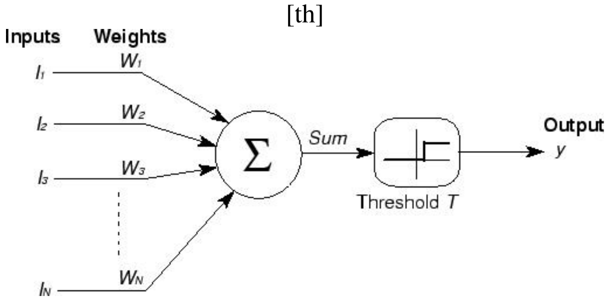


Figure 1. McCulloch-Pitts neuron model

munity of researchers interested in the new science of cybernetics. They were aimed at introducing new terms, such as information and feedback, into many disciplines, including biology, physiology, sociology, ecology, economics, politics, psychoanalysis, linguistics.

At that time, well-known mathematicians and engineers C.Shannon, J.von Neumann, W.R.Ashby, G.Walther, W.Pitts and others also attended these conferences. W.McCulloch usually presided. Ten such conferences took place before 1953. In 1953, it so happened that McCulloch quarreled with Wiener. In the literature, you can find details that we will not dwell on. The fact is that the personal relationship of two outstanding scientists led to the fact that the conferences stopped. Wiener has simply not spoken to McCulloch since. The careers of McCulloch and Pitts, who was also in this circle, did not go up further, but rather broke down. Both died in 1969. At the same time, cybernetic ideas developed not only under the guidance and in the environment of Wiener, but also in other scientific circles. Among such achievements in the fifties, the following should be noted. In 1952, Arthur Samuel created the first checkers game program for the IBM 701. In 1955, Samuel added the ability to self-study to the program. In 1954, the so-called Georgetown experiment was carried out to demonstrate the capabilities of machine translation, (New York, IBM headquarters). During the experiment, a fully automatic translation of more than 60 sentences from Russian into English was demonstrated. In 1956, Allen Newell and Herbert Simon created the program "Logic Theorist", which proved 38 of the 52 theorems from Chapter 2 of Russell and Whitehead's work "Principia Mathematica". Computers were already actively developing at that time and were helping to carry out various studies that were previously impossible. The first books appeared, among them the collection "Automata", published by McCarthy and Shannon ("Automata Studies", Edited by McCarthy and Shannon) in 1956. This collection was almost immediately translated into Russian and disseminated in the USSR, where the rejection of cybernetics was already ending at that time. There rose a desire to hold other meetings and seminars dedicated to this science. A group of scientists organized the Dartmouth Seminar in 1956, which was known for the fact that the term artificial Intelligence was born there. The main organizer was John McCarthy, also young, he was below thirty years old. Among the participants were already well-known experts by that time: Claude Shannon, Marvin Minsky, Alan Newell and others, many of those who authored the top achievements of those times in this field.

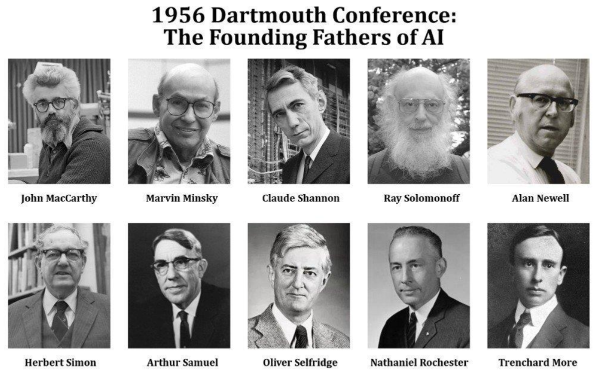


Figure 2. The Founding Fathers and II. (Courtesy of scienceabc.com)

It is important to note what John McCarthy said about the specifics of the Dartmouth seminar: "As for me, one of the reasons for the invention of the term "artificial intelligence" is to avoid association with "cybernetics". The connection with analog feedback seemed erroneous, and I didn't want to accept Wiener as a guru or argue with him" [McCarthy, 1988], in which he specifically traced the history of the creation of these two fields: cybernetics and artificial intelligence. This is the key point, the organizers of the seminar wanted to separate themselves from Wiener, from cybernetics. In addition, the people who gathered at the Dartmouth seminar motivated this desire with a scientific reason. "Newell recalled that since the mid-1950s cybernetics has been divided with AI according to the principles of "symbolic vs. continuous systems" and "psychology vs. neurophysiology" [Newell, 1983].

Indeed, the people who gathered at Dartmouth spoke the language of logic, the language of discrete systems and discussed mathematical models related to automata, languages, logic, graphs, codes, combinatorics. On the contrary, they rejected such continuous mathematical concepts as topology, metrics, real numbers, fields, differential equations, continuous functions. One can argue with this, but it was so. This is the story. The area of artificial intelligence was born in an attempt to separate itself from cybernetics [Kline,2011].

The name that is now appropriate to mention is neurophysiologist Frank Rosenblatt, the creator of the first neurocomputer, named by him "perceptron". The model was first created on paper, and then implemented in hardware.

He actually took the McCulloch-Pitts neuron and organized the tuning or adaptation of this model, suggested

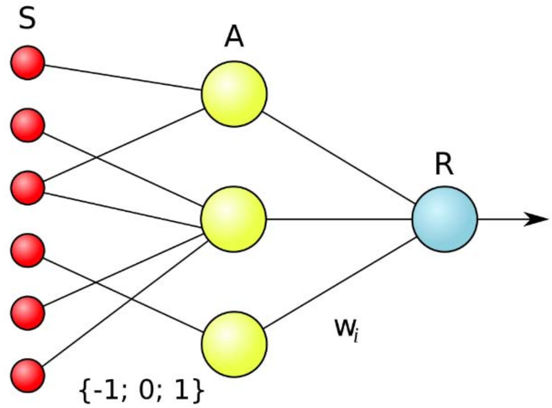


Figure 3. Rosenblatt's Perceptron.

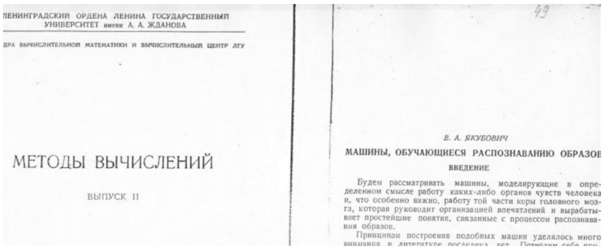
adjusting weights in this model. Moreover, he chose a rule known in psychology as the Hebb rule for learning. The famous psychologist Donald Hebb in his work "Organization of behavior" in 1949 for the first time described algorithms for training human neurons. Hebb's rule (algorithm) is very simple: $\Delta w_i = \gamma x_i y$, where x_i are the input signals of the neuron, y is the output signal (error), w_i are the weights, $\gamma > 0$ is the gain. We will not comment on this rule in detail, but it underlies almost all learning and adaptation algorithms, and it has been repeatedly applied in the future.

Hebb's ideas were further developed by Frank Rosenblatt. In 1957, he proposed a scheme for a device that simulates human perception and called it a "perceptron" (from Lat. perceptio – perception). We emphasize that Frank Rosenblatt was also young and ambitious, he was not yet 30 years old. In the future, these ideas were picked up by many, but not by those who were engaged in artificial intelligence. At the conference following the Dartmouth Seminar in Teddington in 1968, Rosenblatt's results were criticized. Despite the fact that Rosenblatt had many followers, but there were also those who criticized him. Let's now turn to what happened with the development of cybernetics and artificial intelligence in the USSR. There were many attacks on cybernetics in the USSR in the early 1950s. Here, for example, is what was written in the Brief Philosophical Dictionary in 1954. (http://vivovoco.rsl.ru/VV/PAPERS/BIO/CYBER.HTM): "Cybernetics is a reactionary pseudoscience that emerged in the United States after World War II and has become widespread in other capitalist countries, a form of modern mechanicism." Nevertheless, computer technology was actively developing. In 1955, the first computers in continental Europe were built. Articles by experts on cybernetics began to be published. An important role was played by the articles of S.L.Sobolev, A.I.Kitov, A.A.Lyapunov and A.N.Kolmogorov in the BSE in 1958. In 1958-60, the first departments of cybernetic profile began to be created (A.A.Markov, Moscow State University mat.logic) to publish the first books (I.Poletaev "Signal") In 1958, the book by N. Wiener was translated. In 1959, the Scientific Council on the Complex problem of "Cybernetics" was established at the Presidium of the USSR Academy of Sciences, which was chaired by Academician A.I.Berg). The article [Pospelov, 1998] provides a fairly complete picture of this period.

3 The spring of cybernetics and AI: the 1960s

In the 1960s, the development of research on pattern recognition, learning, and cybernetics, in general, was very active. Research activity in the USSR was stimulated by information about research in the West. Books and collections of translations of articles by leading Western scientists were published. Research in the USSR correlated with the world, domestic scientists referred to the works of F. Rosenblatt, G.Sebestian, B.Widrow on pattern recognition systems, adaptive filtering, etc. Fuzzy systems (L.Zadeh – (1965), virtual interlocutors (ELIZA D. Weizenbaum (1966), etc.) were introduced into the circulation of research. Original works and achievements in pattern recognition appeared: the "Bark" algorithm (M.Bongard, 1961), the method of potential functions (M.Aizerman, E.Braverman, L.Rozonoer (1963-1964)), recognition algorithms based on the separation of convex sets (V.Yakubovich (1963-1966); A.Lerner, V.Vapnik, A.Chervonenkis (1963, 1964)). Works on artificial intelligence also were going on: (D.A.Pospelov (1966, 1972, 1976 and later), G.S.Pospelov, M.L.Tsetlin, V.N.Zakharov, V.F.Khoroshevsky, E.V.Popov. In Leningrad, research was developing on machine translation of texts (G.S.Tseytin (1959)) and automatic. proof of theorems (the inverse method of Maslov, S.Y.Maslov (1964). In the winter of 1961-62, M.L. Tsetlin, M.M. Bongard and V.I. Varshavsky organized the first winter school-seminar on automata theory and pattern recognition in Komarovo near Leningrad.

Activities in the field of cybernetics were also actively conducted in Leningrad. In November 1956, the Cybernetics Section of the House of Scientists was founded, the first chairman of which was the future Nobel laureate L.V.Kantorovich. The section became the first public scientific organization in the field of cybernetics in the USSR. In 1959, V.A.Yakubovich created a laboratory of theoretical cybernetics at Leningrad State University (LGU). A number of departments in the field of automation and technical cybernetics have been created also at other technical universities: Military Academy named after Mozhaisky (E.P.Popov), Electrotechnical university (LETI) (I.Timofeev, A.Vavilov, V.Smolov), Leningrad Polytechnic Institute (A.I.Lurie). S.A.Mayorov's group in Leningrad Institute of Fine Mechanics and Optics (LITMO) was awarded the USSR State Prize in 1969 for the development of the UM1-NX controlling computer.



ЛЕНИНГРАДСКИЙ ОРДЕНА ЛЕНИНА ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ имени А. А. ЖДАНОВА

ДРА ВЫЧИСЛИТЕЛЬНОЙ МАТЕМАТИКИ И ВЫЧИСЛИТЕЛЬНЫЙ ЦЕНТР ЛГУ

МЕТОДЫ ВЫЧИСЛЕНИЙ

ВЫПУСК II

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В. А. ЯКУБОВИЧ

МАШИНЫ, ОБУЧАЮЩИЕСЯ РАСПОЗНАВАНИЮ ОБРАЗОВ

ВВЕДЕНИЕ

Будем рассматривать машины, моделирующие в определенном смысле работу каких-либо органов чувств человека и, что особенно важно, работу той части коры головного мозга, которая руководит организацией впечатлений и вырабатывает простейшие понятия, связанные с процессом распознавания образов.

Принципам построения подобных машин уделялось много

Figure 4. Title page of Yakubovich's 1963 paper

4 Contributions of V.A. Yakubovich to machine learning, pattern recognition, adaptive systems and robots

Let us dwell in more detail on the works of Vladimir Yakubovich. His publications are mainly related to control theory, stability theory, optimal control, and the study of nonlinear systems. These are his most famous achievements. And the achievements in the field of adaptive systems, the theory of learning systems are less well known. But they will be mainly discussed because in the field of mathematical cybernetics, his work was fundamental, had a continuation and was picked up by other scientists. The research took place in the V.A. Yakubovich's group that worked in the Laboratory of Theoretical Cybernetics, and since 1970 – also at the Department of Theoretical Cybernetics of the Faculty of Mathematics and Mechanics of Leningrad University. Let us discuss the first articles that appeared in university publications and in Reports of the USSR Academy of Sciences: [Yakubovich, 1963; Yakubovich, 2021; Yakubovich, 1965; Yakubovich, 1965; Yakubovich, 1966; Yakubovich, 1968; Yakubovich, 1968].

The 1963 article [Yakubovich, 1963] turned out to be one of the first where the terms "machine learning" and " learning machines" were actively used. Currently, the journal "Vestnik of St. Petersburg University" has reprinted this article [Yakubovich, 1963], see [Yakubovich, 2021] and it has been translated into English, which will undoubtedly contribute to the dissemination of V.A. Yakubovich's ideas and methods in this field. In just fifteen years from 1963 to 1978, V.A. Yakubovich published 45 articles in the field of artificial intelligence, adaptive and learning systems and pattern recognition. In total, during this period, he published 105 articles. This means that almost half of them were devoted to the issues of machine learning and artificial intelligence, adaptive systems, learning and recognition algorithms. Thus, in those years artificial intelligence and adaptation occupied an essential place in the work of V.A. Yakubovich. It should be noted that in recent decades pattern recognition and learning have played a central role in the field of artificial intelligence. Some time ago, this was not the case, and many works of this orientation were considered related to cybernetics as a broader field. The list of the main works of V.A. Yakubovich on machine learning, recognition, adaptive systems and robots is as follows [Yakubovich, 1963; Yakubovich, 2021; Yakubovich, 1965; Yakubovich, 1966; Yakubovich, 1968; Yakubovich, 1968; Gelig and Yakubovich, 1968; Yakubovich, 1968; Yakubovich, 1970; Penev and Yakubovich, 1971; Yakubovich and Timofeev, 1971; Timofeev, Kharichev, Shmidt and Yakubovich 1971; Gusev, Timofeev and Yakubovich, 1977].

We will comment on the nature of V.A. Yakubovich's results by the example of his article "Machines learning to recognize images" [Yakubovich, 1963].

This article was essentially the first on machine learning in the Soviet Union. Even in the world, this article was one of the first. A similar article by V.N.Vapnik with an identical title was published ten years later [Vapnik , 1973]. And in Leningrad, the article [Yakubovich, 1963] was indeed the first article on this topic.

Let's briefly consider the problem of pattern recognition from this article using the example of face recognition. Suppose there are two samples, male and female faces, and it is necessary to learn how to distinguish female faces from male ones. In other words, to learn how to respond to the presented new image: is it a male or a female face.

Most approaches to solving the problem begin with digitizing images: numerical features are introduced: $x{=}(x_1, x_2, ..., x_m)$, coordinates of objects are calculated: $X_k{=}(x_{k1}, x_{k2}, ..., x_{km})$, $k = 1, ..., N$, and the function $y(x)$ is defined specifying the class number, $y(x) = -1{-}M, y(x) = +1{-}F$.

Usually, signs are introduced so that the problem is translated into a Euclidean space with a Euclidean metric, in which two sets with corresponding coordinates need to be separated. How to separate them? The first thing that comes to mind is to divide by a plane.

Figure 5. Left –male faces, right – female faces

A hyperplane $(w, x) + d = 0, w = (w_1, w_2, ..., w_m)$ will be called separating two finite sets if all points of one set are on one side of the hyperplane, and all points of the other set are on the other one. Sometimes two sets cannot be separated by a hyperplane in a multidimensional space. In the case, when the separating hyperplane exists it is often desirable to find the separating plane optimal in some sense. It is possible to generalize the problem, and seek for separating linear combination of given nonlinear

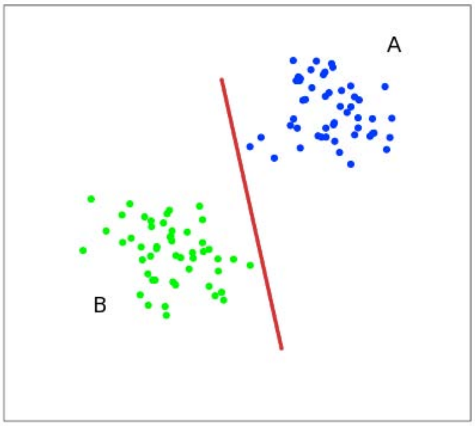
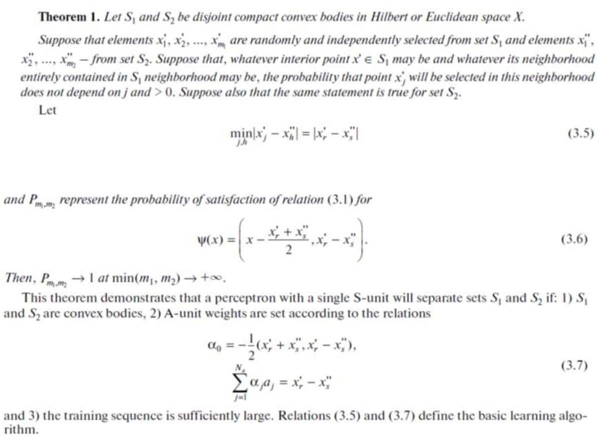


Figure 6. Separating hyperplane

functions with adjustable weights. To find algorithms for adjusting the coefficients of the separating hyperplane is the task that needs to be solved. During the learning stage, the pictures each of which is a point in a multidimensional space, are shown to the machine sequentially, And the machine must build a separating plane according to the points presented to it. The main result of the article is an algorithm for constructing a separating hyperplane, as well as the conditions under which this algorithm gives a solution. Moreover, the solvability conditions of the problem are given in terms of probability distributions of points over given sets, assuming that these sets are separable by a hyperplane. Under certain assumptions about the distributions of these points over the sets, it is shown that the proposed algorithm allows one to construct a separating hyperplane with probability one. For formulation of the corresponding theorem see Fig.7.

V.A Yakubovich, VESTNIK ST. PETERSBURG UNIVERSITY, MATHEMATICS Vol. 54, No. 4, 2021.



Theorem 1. *Let S_1 and S_2 be disjoint compact convex bodies in Hilbert or Euclidean space X.*

Suppose that elements $x_1', x_2', \ldots, x_{m_1}'$ are randomly and independently selected from set S_1 and elements $x_1'', x_2'', \ldots, x_{m_2}''$ – from set S_2. Suppose that, whatever interior point $x' \in S_1$ may be and whatever its neighborhood entirely contained in S_1 neighborhood may be, the probability that point x_j' will be selected in this neighborhood does not depend on j and > 0. Suppose also that the same statement is true for set S_2.

Let

$$\min_{j,h}|x_j' - x_h''| = |x_r' - x_s''| \quad (3.5)$$

and P_{m_1,m_2} represent the probability of satisfaction of relation (3.1) *for*

$$\psi(x) = \left(x - \frac{x_r' + x_s''}{2}, x_r' - x_s''\right). \quad (3.6)$$

Then, $P_{m_1,m_2} \to 1$ *at* $\min(m_1, m_2) \to +\infty$.

This theorem demonstrates that a perceptron with a single S-unit will separate sets S_1 and S_2 if: 1) S_1 and S_2 are convex bodies, 2) A-unit weights are set according to the relations

$$\alpha_0 = -\frac{1}{2}(x_r' + x_s'', x_r' - x_s''), \quad \sum_{j=1}^{N_a} \alpha_j a_j = x_r' - x_s'' \quad (3.7)$$

and 3) the training sequence is sufficiently large. Relations (3.5) and (3.7) define the basic learning algorithm.

Figure 7. Formulation of the Yakubovich's theorem

Fig.8 shows how the process of constructing a separating hyperplane takes place. Each time we project the vector of weights of the hyperplane to a new set where there is a solution. These sets are convex, which makes it possible to find a solution in a finite number of steps. Additionally, theorems on the convexity of some specific classes of sets, on the separation of convex hulls of sets, and a theorem on the separation of several even non-convex sets are given in the paper.

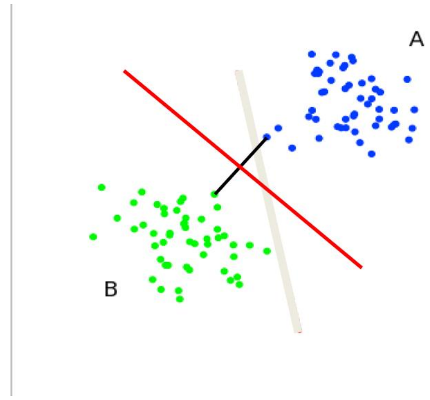


Figure 8. Geometry of Yakubovich's algorithm

$$(w, x) + d < 0, ||X_r^{'} - X_s^{"}|| = \min_{i,j} ||X_i^{'} - X_j^{"}||$$
$$X_i^{'} \in A, X_j^{"} \in B.$$
$$w = X_r^{'} - X_s^{"}, d = -0.5(X_r^{'} + X_s^{"}, X_r^{'} - X_s^{"}).$$

The results obtained were applied to practical tasks in the field of criminology: the problem of handwriting recognition was considered [Kozinets, Lantsman, and Yakubovich, 1966]. To solve it, signatures of different people are encoded using dots affixed to them in characteristic places. Accounting for errors, if they are contained in the triangles shown in the figure, when writing numbers or letters, they turn out to form convex sets. The coordinates of these points, taking into account this uncertainty, allow us to justify the proposed algorithm for solving this particular problem.

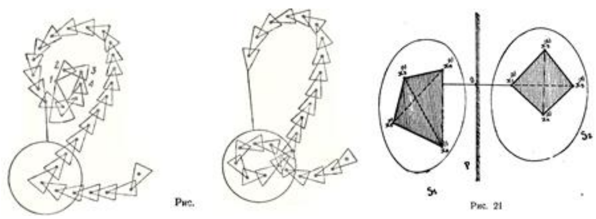


Figure 9. Handwriting pattern recognition

Now about other approaches for solving the problem of separating sets. This well-known problem of com-

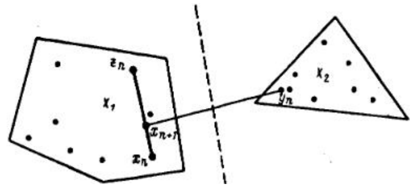


Figure 10. Geometry of Kozinets's algorithm

putational mathematics has been used in machine learning since the 1960s. Let us mention the result of B.N. Kozinets, a coworker of V.A. Yakubovich on the optimal algorithm for separating convex sets [Kozinets, 1964].

Regardless of this, the group of V.F. Demyanov and V.N. Malozemov at LGU was engaged in similar tasks and received another fairly well-known algorithm called MDM [Mitchel, Dem'yanov and Malozemov, 1971; Mitchel, Dem'yanov and Malozemov, 1974; Malozemov, 2012].

But most of all, the algorithm proposed in Moscow in 1963-1964 by V.N.Vapnik became known, which gave rise to a whole method – the Support Vector Machine method (SVM). This method has become incredibly popular since the 1990s. V.N. Vapnik, a Russian-born scientist living in the USA, now has a citation index exceeding 250,000 [Vapnik and Chervonenkis, 1964]. Thus, the problem was solved for the first time by Moscow scientists and in Leningrad by V.A. Yakubovich's group. V.A.Yakubovich was also interested in other tasks: the task of adaptive control, adaptive robots. It was V.A.Yakubovich who first introduced the term "robot" into the scientific literature. This term first appeared in 1968 in an article in the Reports of the USSR Academy of Sciences. The task was set: to build a smart (reasonable) robot. Precise definitions are given of what a robot is, what is reasonable, and an algorithm is built controlling the robot. Theorems are proved that say that a robot is built that is reasonable in a given class of conditions.

Thus, V.A.Yakubovich formulated and proved the first theorem of mathematical robotics: when certain conditions are met, the simplest robot is reasonable in a given class of tasks. Similar theorems are obtained for different classes of robots. These tasks were quite simple, stylized. But that was the beginning. These were the first robotics theorems.

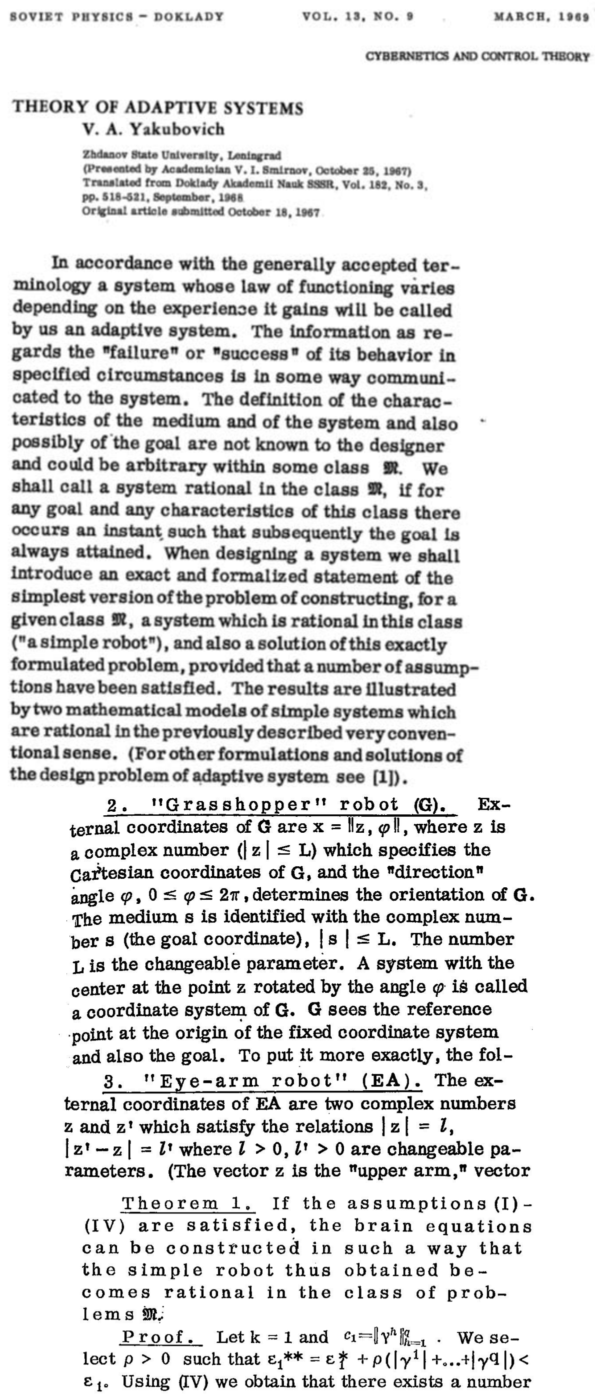
Further, more complex tasks were considered, the work became more complicated. The robot "hawk" can represent a stylized flight of some kind of aircraft. The tasks of the robot "cyclist" and others were considered.

Let us now illustrate the method of recurrent objective inequalities (ROI) proposed by V.A. Yakubovich in the article [Yakubovich, 1966], which formed the basis for solving many problems of pattern recognition, adaptation, control, design of robots, etc. Return to the problem of face recognition and consider the space of hyperplanes The geometry of YAVA algorithm [Yakubovich, 1966] is presented in Fig.13. It projects the current vector of weights wk onto a new hyperplane corresponding to the newly shown image.

One of the most famous algorithms of the Yakubovich method is "Stripe". The problem is to find a solution of the infinite system of inequalities:

One of the most famous algorithms of the Yakubovich method is "Stripe". The problem is to find a solution of the infinite system of inequalities:

Similar tasks were solved in those years almost simultaneously in Moscow and Leningrad. The well-known



SOVIET PHYSICS – DOKLADY VOL. 13, NO. 9 MARCH, 1969

CYBERNETICS AND CONTROL THEORY

THEORY OF ADAPTIVE SYSTEMS

V. A. Yakubovich

Zhdanov State University, Leningrad
(Presented by Academician V. I. Smirnov, October 25, 1967)
Translated from Doklady Akademii Nauk SSSR, Vol. 182, No. 3, pp. 518-521, September, 1968
Original article submitted October 18, 1967

In accordance with the generally accepted terminology a system whose law of functioning varies depending on the experience it gains will be called by us an adaptive system. The information as regards the "failure" or "success" of its behavior in specified circumstances is in some way communicated to the system. The definition of the characteristics of the medium and of the system and also possibly of the goal are not known to the designer and could be arbitrary within some class 𝔐. We shall call a system rational in the class 𝔐, if for any goal and any characteristics of this class there occurs an instant such that subsequently the goal is always attained. When designing a system we shall introduce an exact and formalized statement of the simplest version of the problem of constructing, for a given class 𝔐, a system which is rational in this class ("a simple robot"), and also a solution of this exactly formulated problem, provided that a number of assumptions have been satisfied. The results are illustrated by two mathematical models of simple systems which are rational in the previously described very conventional sense. (For other formulations and solutions of the design problem of adaptive system see [1]).

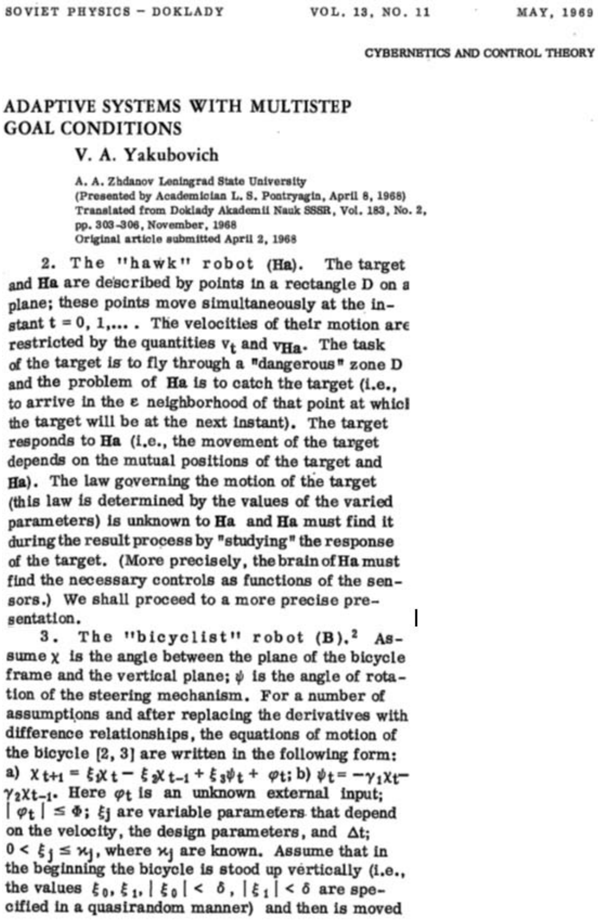
2. "Grasshopper" robot (G). External coordinates of G are $x = \|z, \varphi\|$, where z is a complex number ($|z| \leq L$) which specifies the Cartesian coordinates of G, and the "direction" angle φ, $0 \leq \varphi \leq 2\pi$, determines the orientation of G. The medium s is identified with the complex number s (the goal coordinate), $|s| \leq L$. The number L is the changeable parameter. A system with the center at the point z rotated by the angle φ is called a coordinate system of G. G sees the reference point at the origin of the fixed coordinate system and also the goal. To put it more exactly, the fol-

3. "Eye-arm robot" (EA). The external coordinates of EA are two complex numbers z and z' which satisfy the relations $|z| = l$, $|z' - z| = l'$ where $l > 0$, $l' > 0$ are changeable parameters. (The vector z is the "upper arm," vector

Theorem 1. If the assumptions (I)-(IV) are satisfied, the brain equations can be constructed in such a way that the simple robot thus obtained becomes rational in the class of problems 𝔐.

Proof. Let k = 1 and $c_1 = \|\gamma^h\|_{h=1}^q$. We select $\rho > 0$ such that $\varepsilon_1^{**} = \varepsilon_1^* + \rho(|\gamma^1| + \ldots + |\gamma^q|) < \varepsilon_1$. Using (IV) we obtain that there exists a number

Figure 11. First theorem of robotics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CYBERNETICS AND CONTROL THEORY

ADAPTIVE SYSTEMS WITH MULTISTEP GOAL CONDITIONS

V. A. Yakubovich

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(Presented by Academician L. S. Pontryagin, April 8, 1968)
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2. The "hawk" robot (Ha). The target and Ha are described by points in a rectangle D on a plane; these points move simultaneously at the instant t = 0, 1,... . The velocities of their motion are restricted by the quantities v_t and v_{Ha}. The task of the target is to fly through a "dangerous" zone D and the problem of Ha is to catch the target (i.e., to arrive in the ε neighborhood of that point at which the target will be at the next instant). The target responds to Ha (i.e., the movement of the target depends on the mutual positions of the target and Ha). The law governing the motion of the target (this law is determined by the values of the varied parameters) is unknown to Ha and Ha must find it during the result process by "studying" the response of the target. (More precisely, the brain of Ha must find the necessary controls as functions of the sensors.) We shall proceed to a more precise presentation.

3. The "bicyclist" robot (B).[2] Assume χ is the angle between the plane of the bicycle frame and the vertical plane; ψ is the angle of rotation of the steering mechanism. For a number of assumptions and after replacing the derivatives with difference relationships, the equations of motion of the bicycle [2, 3] are written in the following form: a) $\chi_{t+1} = \xi_1\chi_t - \xi_2\chi_{t-1} + \xi_3\psi_t + \varphi_t$; b) $\psi_t = -\gamma_1\chi_t - \gamma_2\chi_{t-1}$. Here φ_t is an unknown external input; $|\varphi_t| \le \Phi$; ξ_j are variable parameters that depend on the velocity, the design parameters, and Δt; $0 < \xi_j \le \varkappa_j$, where $\varkappa_j$ are known. Assume that in the beginning the bicycle is stood up vertically (i.e., the values $\xi_0, \xi_1, |\xi_0| < \delta, |\xi_1| < \delta$ are specified in a quasirandom manner) and then is moved

Figure 12. Advanced robots

scientist Ya.Z. Tsypkin from the Institute of Control Problems of the USSR Academy of Sciences, in his book [Zypkin, 1968] managed to systematize the results obtained based on the approach of minimizing empirical risk and using the stochastic approximation method and show that different methods differ only in the choice of some target functionals, which actually leads to algorithms of the same class.

These algorithms can be considered as a generalization of the Rosenblatt perceptron, although they were obtained from completely different considerations and different mathematical results were behind these algorithms. In particular, it was discovered and presented. the analogy between the algorithms of Aizerman, Braverman, Rozonoer, Yakubovich, Vapnik and colleagues, the main ones are presented in the tables in the Tsypkin's book. It is very interesting and important that adaptation and training in those years were very close, there was practically no difference between them. The same algorithms were proposed to be used in recognition, identification, control, evaluation, filtering, and a variety of other cybernetic tasks.

The conviction was growing that the people who were engaged in these algorithms were also engaged in the creation of intelligent systems. However, other specialists worked with other methods and there was still some separation of those who were engaged in artificial intelligence and cybernetics. Although the tasks were often very close. It has become especially clear in recent years that the tasks are close and the methods of solving them may be the same.

The results obtained in those years were exposed in monographs published by V.A. Yakubovich and his coworkers in the USSR [Fomin, 1976; Timofeev, 1978; Fomin, Fradkov and Yakubovich, 1981; Gelig, 1982; Granovskaya, 1991].

In 1996 V.A. Yakubovich was awarded with IEEE Control Systems Award - the main annual prize for control systems of the IEEE (Institute of Electrical and Electronics Engineers) and the medal "for pioneering and fundamental achievements in the theory of stability and optimal control". There was a very big conference in Japan (CDC'96), where the award was presented and Vladimir Yakubovich made a speech. It is worth mentioning that nothing was said in the award citation about cybernetics, adaptive systems, artificial intelligence. Indeed, V.A. Yakubovich had outstanding achievements in the field of optimal control. But the value of his works on cybernetics and artificial intelligence is still a little underestimated.

One must say about the significance of the works that were briefly listed. There are actually a lot of them and one can talk about them for a long time. But from the point of view of history, it is important what role they

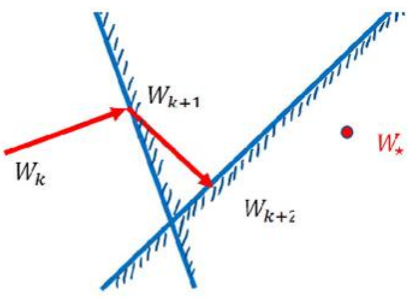
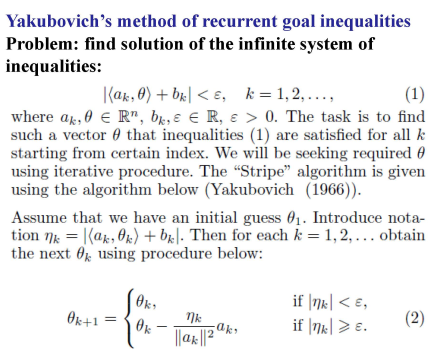


Figure 13. Geometry of YAVA algorithm


Yakubovich's method of recurrent goal inequalities

Problem: find solution of the infinite system of inequalities:

$$|\langle a_k, \theta\rangle + b_k| < \varepsilon, \quad k = 1, 2, \ldots, \qquad (1)$$

where $a_k, \theta \in \mathbb{R}^n$, $b_k, \varepsilon \in \mathbb{R}$, $\varepsilon > 0$. The task is to find such a vector θ that inequalities (1) are satisfied for all k starting from certain index. We will be seeking required θ using iterative procedure. The "Stripe" algorithm is given using the algorithm below (Yakubovich (1966)).

Assume that we have an initial guess θ_1. Introduce notation $\eta_k = |\langle a_k, \theta_k\rangle + b_k|$. Then for each $k = 1, 2, \ldots$ obtain the next θ_k using procedure below:

$$\theta_{k+1} = \begin{cases} \theta_k, & \text{if } |\eta_k| < \varepsilon, \\ \theta_k - \dfrac{\eta_k}{\|a_k\|^2} a_k, & \text{if } |\eta_k| \geqslant \varepsilon. \end{cases} \qquad (2)$$

Figure 14. "Stripe" algorithm.

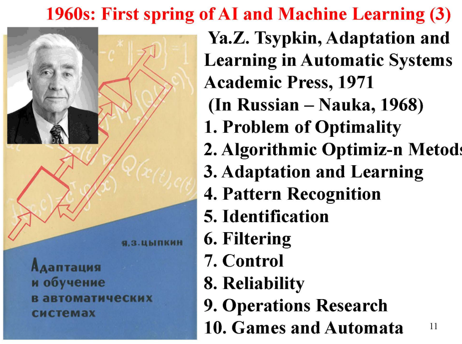


Figure 15. Tsypkin's 1968 book contents

Table 4.1

TYPICAL ALGORITHMS OF TRAINING

Number	Functional	Algorithms	Comments	Authors
1	$J(\mathbf{c}) = M\{(\operatorname{sgn} y - \operatorname{sgn} \mathbf{c}^T\boldsymbol{\phi}(\mathbf{x}))\mathbf{c}^T\boldsymbol{\phi}(\mathbf{x})\}$	$\mathbf{c}[n] = \mathbf{c}[n-1] + \gamma[n](\operatorname{sign} y[n] - \operatorname{sign} \mathbf{c}^T[n-1] \times \boldsymbol{\phi}(\mathbf{x}[n]))\boldsymbol{\phi}(\mathbf{x}[n])$		Aizerman, Braverman, Rozonoer, Yakubovich
2	$J(\mathbf{c}) = M\{\lvert y - \mathbf{c}^T\boldsymbol{\phi}(\mathbf{x})\rvert\}$	$\mathbf{c}[n] = \mathbf{c}[n-1] + \gamma[n] \operatorname{sign} (y[n] - \mathbf{c}^T[n-1] \times \boldsymbol{\phi}(\mathbf{x}[n]))\boldsymbol{\phi}(\mathbf{x}[n])$		Aizerman, Braverman, Rozonoer
3	$J(\mathbf{c}) = M\{(y - \mathbf{c}^T\boldsymbol{\phi}(\mathbf{x}))^2\}$	$\mathbf{c}[n] = \mathbf{c}[n-1] + \gamma[n](y[n] - \mathbf{c}^T[n-1] \times \boldsymbol{\phi}(\mathbf{x}[n]))\boldsymbol{\phi}(\mathbf{x}[n])$	L-optimality according to Yakubovich	Aizerman, Braverman, Rozonoer, Yakubovich
		$\mathbf{c}[n] = \mathbf{c}[n-1] + \Gamma[n](y[n] - \mathbf{c}^T[n-1] \times \boldsymbol{\phi}(\mathbf{x}[n]))\boldsymbol{\phi}(\mathbf{x}[n])$	$y = \begin{cases} 1 & \text{if } \mathbf{x}[n] \in A \\ 0 & \text{if } \mathbf{x}[n] \notin A \end{cases}$ $\Gamma^{-1}[n] = \Gamma^{-1}[n-1] - \boldsymbol{\phi}\boldsymbol{\phi}^T$	Blaydon, Ho
4	$J(\mathbf{c}) = M\{R(D(\mathbf{x})) - \overline{R(\mathbf{c}^T\boldsymbol{\phi}(\mathbf{x}))}\mathbf{c}^T\boldsymbol{\phi}(\mathbf{x})\}$	$\mathbf{c}[n] = \mathbf{c}[n-1] + \gamma[n][R(D(\mathbf{x}[n])) - \overline{R(\mathbf{c}^T[n-1] \times \boldsymbol{\phi}(\mathbf{x}[n]))}] \times \boldsymbol{\phi}(\mathbf{x}[n])$	$R(D(\mathbf{x}))$ is an operator of a random experiment with two outcomes: $+1$ with probability $D(\mathbf{x})$, and -1 with probability $1 - D(\mathbf{x})$	Aizerman, Braverman, Rozonoer
5	$J(\mathbf{c}) = \sum_{i=1}^{l} F^2(1 - \mathbf{c}^T\mathbf{k}^i) + \sum_{j=l+1}^{N} F_2{}^2(k - \mathbf{c}^T\mathbf{k}^j)$	$\frac{dc_i(t)}{dt} = \gamma(t)F_1(1 - \mathbf{c}^T(t)\mathbf{k}^i) \times F_1(1 - \mathbf{c}^T(t)\mathbf{k}^i),\ (1 \le i \le l)$ $\frac{dc_j(t)}{dt} = \gamma(t)F_2(k - \mathbf{c}^T)t)\mathbf{k}^k) \times F_2(k - \mathbf{c}^T(t)\mathbf{k}^j),\ (l+1 \le j \le N)$	$F_1(z) = z - \lvert z\rvert,$ $F_2(z) = \lvert z\rvert - z$	Vapnik, Lerner, Chervonenkis

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Figure 16. Table of algorithms

play in today's development of cybernetics and artificial intelligence. The authors' opinion is that there are three main achievements that affect the current state of the science. First of all, these are mathematical statements of problems in the theory of learning and adaptive systems. They are already being used and have become so accustomed to our research that we often do not refer to the works of Yakubovich, in which these productions appeared for the first time. The second direction is the method of solving Recurrent Objective Inequalities (ROI), based on the reduction of the initial problem to solving ROI. This method is less known but it has great application potential since it has now become clear that learning and adaptive systems, are very close areas in the booming field of artificial intelligence. The

Figure 17. CDC-96, Kobe, Japan,1996. Vladimir with colleagues.

third area, which was even less fortunate, is adaptive suboptimal control. We will indicate the first two articles on this topic [Yakubovich, 1976; Bondarko and Yakubovich, 1982]. Even before the appearance of these articles, adaptive optimal control was studied in different cities in the Soviet Union and abroad, too. But if we are talking about mathematical achievements, then, perhaps, these two articles by Yakubovich should be considered fundamental ones.

They should be highlighted because they have anticipated an important current area of reinforcement learning which is very active and popular in recent decades. Let us explain this in more detail. Now in the field of machine learning, reinforcement learning is an important direction. It is also used by those who are engaged in artificial intelligence and machine learning that are not related to control tasks, In recent years its connection with control tasks has been discovered. Here are several fundamental works at the intersection of control theory and the theory of learning systems. They have been published in reputable international publications and have several hundred citations over the past ten years [Lewis and Vrabie, 2009; Lewis, Vrabie and Vamvoudakis, 2012; Sutton, Barto and Williams, 1992; Yang, Liu and Wang, 2014; Recht, 2019]. The number of papers which use the methods of "reinforcement learning" exceeds a thousand. The meaning of this activity is that a very close connection has been established and the task of adaptive optimal control can be solved using reinforcement learning methods. Adaptive optimal control occurs when you want to achieve optimality with unknown parameters of unknown models, maybe of the control system too. It is important that the methods developed by Yakubovich still in the 1970s can be applied here. It is interesting that rigorous proof of the reinforcement learning and adaptive dynamic programming in onlinear case was obtained only recently [Bian and Jiang, 2021].

5 Bregman's method: search of intersection of convex sets

Another powerful method was proposed in 1964 in LGU by young mathematician Lev Bregman (he was

Figure 18. CDC-96, Kobe, Japan,1996 (IEEE Control System Award Ceremony)

23 years old in 1964). Bregman proposed a recurrent algorithm for finding a point in the intersection of the finite number of convex sets in a Hilbert space. The problem was motivated by an application problem of city planning that had nothing to do with learning. The Bregman's method consisted in evaluation of consecutive projections onto the nearest point of the set taken in the cyclic order (Fig.18). Weak convergence of the projections to the intersection of all sets was proved in the paper cite46 (the paper was recommended to publication by Leonid Kantorovich, future Nobel prize winner). It is interesting that Yakubovich's method ROI is also applicable to this problem.

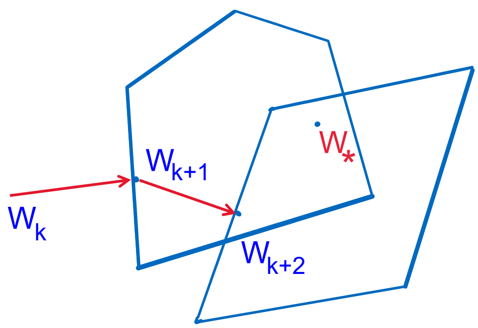

Figure 19. Bregman's projection algorithm

In his next paper [Bregman, 1966] Bregman proposed a useful functional transformation. Let $f(x)$ be a strictly convex twice differentiable function, $x \in R^n$. Let $D(x,y) = f(x) - f(y) - (gradf(y), x - y)$, where $gradf(x)$ is the gradient of the function $f(x)$. Function $D(x,y)$ turns out to be convenient to use for the convergence proofs as the Lyapunov function candidate. It was later called *Bregman divergence*. In the paper cite48 Bregman extended his previous results to present an elegant framework for convex optimization. It was later widely used for machine learning, clusterization, image deblurring, image segmentation, data reconstruction, etc.

The terms *Bregman divergence* and *Bregman method* are now widely used: the number of the papers in the journals indexed in Scopus that have those terms (and related terms *Bregman projection*, *Bregman iteration*, etc. in the paper titles exceeds 900 in October, 2022. As for the paper [Bregman, 1967] itself it has more than 1500 citations in Scopus. It is interesting that in the paper by [Gubin, Polyak, and Raik, 1967] a similar problem was studied and a number of results on strong convergence and convergence rate in Hilbert space were obtained without use of Bregman divergence. Also algorithms with incomplete relaxation were proposed and convergence in a finite number of steps was established as well as some applications to Chebyshev approximation and optimal control. The results of the paper by [Gubin, Polyak, and Raik, 1967] are also used by many authors in machine learning and related areas of optimization: it has more then 500 citations in Scopus. It is good to know that a number of ideas and algorithms proposed by B.T.Polyak are demanded in machine learning currently. One can mention optimization algorithms with accelerated convergence: 'heavy ball' method [Polyak , 1964], accelerated stochastic approximation [Polyak and Juditsky, 1992], etc.

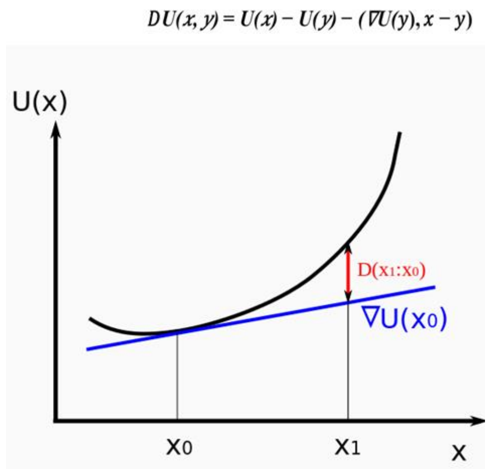

Figure 20. Bregman's divergence

6 Looking into the future

Trying to look into the future, we note an important trend. In recent years, cybernetics, which was not very popular at the turn of the eighties, nineties and even at the beginning of this century, has given way to a fashionable place at the head of these sciences in the public world view to computer science. Computer science has become the leading, the main term in our field. And now artificial intelligence has eclipsed everything else. But at the same time, it is noted in a number of publications that cybernetics has not completely disappeared, but it is returning. The term "return of cybernetics" in the preface to the special issue of the new journal on machine intelligence, which is dedicated to the human-machine interface [Editorial, 2019]. The brain-computer interface, the human-machine interface is the area of cybernetics that is now gaining momentum. Cybernetic methods can also be applied here, including those discussed. It is important that such an integration is observed, cybernetics and artificial intelligence do not diverge, do not overshadow each other, although the number of publications on artificial intelligence is orders of magnitude greater than in the conventional areas of cybernetics. As a result, the term cybernetics became less known than artificial intelligence, but there is currently a revival of interest in and appreciation for Wiener's ideas, together with a renewed focus on augmentation of human abilities. Meanwhile, the development of brain–machine or neural interfaces has made substantial progress in the medical sciences since the 1970s, and the synergy with artificial intelligence research this past decade is bringing the different strands of research together.

Experts in the field of control science and in the field of artificial intelligence are interested in interaction. On this topic of interaction between control and training, artificial intelligence, several seminars are currently being held in the world, in which well-known scientists participate. And this is the direction in the future that seems to be developing very actively.

References

A. M. Annaswamy and A. L. Fradkov. (2021). A Historical Perspective of Adaptive Control and Learning. textit Annual Reviews in Control, (52): 18–41.

B Bian, T., and Jiang, Z.-P., (2021). Value iteration, adaptive dynamic programming, and optimal control of nonlinear systems *IEEE Trans. Neur. Net and Learning Systems* .

Bondarko, V.A, and Yakubovich, V.A. (1982). Synthesis of a suboptimal adaptive system with a reference model for controlling a discrete linear dynamic object. *in the collection: Adaptation and training in control and decision-making systems. Novosibirsk: Nauka* . 10-27.

Bregman, L., (1965). Use of consecutive projection for finding a common point of convex sets. *Doklady Akademii Nauk SSSR (recommended by L.V.Kantorovich)*, **162**.

Bregman, L., (1966). Relaxation method of finding a point common to some given convex sets and its use in solving optimization problems. *Doklady Akademii Nauk SSSR*, **171**(5): 1019-1023.

Bregman, L., (1967). The relaxation method of finding the common point of convex sets and its application to the solution of problems in convex programming. *USSR Comp.Math.and Math. Phys*, (7): 200-217.

Editorial, (2019). Return of cybernetics. Editorial. Nature Machine Intelligence. , **1**(Sept. 11): 385.

Fomin V.N. (1976). Mathematical theory of trainable recognition systems. *Izd-vo LGU*

Fomin, V.N., Fradkov, A.L. and Yakubovich, V.A. (1981). Adaptive control of dynamic systems. *M.: Nauka* .

A.L.Fradkov (2008). Scientific School of Theoretical Cybernetics at St. Petersburg (Leningrad) University. *In the book: The History of Computer Science and Cybernetics in St. Petersburg (Leningrad). Edited by R.M.Yusupov*, 79-83.

A.L.Fradkov (2014). Scientific biography of V.A. Yakubovich and his school in St. Petersburg. (Leningrad) University. Special session "Vladimir Andreevich Yakubovich and his scientific school". *XII All-Russian Meeting on Control Problems (VSPU-2014). Moscow, June 16-19, 2014*.

Fradkov, A.L. (2020). Early History of Machine Learning. *IFAC Congress on Automatic Control. Berlin, 12-17 July*.

Gelig, A.Kh. (1982). Dynamics of impulse systems and neural networks. *L.: Izd-vo LGU* .

A.Kh.Gelig, V.A. Yakubovich, (1968). Application of a trainable recognition system to isolate a signal from noise. *Vychislitel"naya tekhnika I voprosy programmirovaniya , L.: Izd-vo LGU* , 95-100.

Granovskaya, R.M. (1991). Intuition and artificial intelligence. *Leningrad, Izd.LGU* .

Gubin L.G., Polyak B.T., Raik E.V., (1967). The method of projections for finding the common point of convex sets. *USSR Computational Mathematics and Mathematical Physics*, **7**(6): 1-24.

Gusev C.V., Timofeev, A.V. and Yakubovich (1977). Adaptation in robotic systems with artificial intelligence. *VII All-Union Meeting on Control Problems. Abstracts of reports. Minsk*, 279-282.

Gusev, S.V., Bondarko V.A. (2020). Notes on Yakubovich's method of recursive objective inequalities and its application in adaptive control and robotics. *IFAC Congress on Automatic Control. Berlin, 12-17 July* .

Ronald R. Kline, (2011). Cybernetics, Automata Studies, and the Dartmouth Conference on Artificial Intelligence. *IEEE Annals of the History of Computing*, **23**: 5-16.

B.N. Kozinets, (1964). About a linear perceptron learning algorithm. *Vychislitel"naya tekhnika I voprosy programmirovaniya , L.: Izd-vo LGU*, **(**3).

B.N. Kozinets, R. M. Lantsman, and V. A. Yakubovich. (1966). Forensic examination of close handwriting using electronic computers. *Dokl. Akad. Nauk SSSR*, **167**:1008-1011.

Lewis, F. and Vrabie, D. (2009). Reinforcement learning and adaptive dynamic programming for feedback control. *IEEE Circ. Syst. Magazine* , **9**(3). Cited by: (697)

Lewis, F., Vrabie, D. and Kyriakos G. Vamvoudakis (2012). Reinforcement Learning and Feedback Control: Using Natural Decision Methods to Design Optimal Adaptive Controllers. *IEEE Circ. Syst. Magazine* , **32**(6). Cited by: (424)

Malozemov, V.N. (2012). MDM method after 40 years. *Vestnik Syktyvkarskogo un-ta* , **(**15).

McCulloch, W. and Pitts, W., (1943). A logical calculus of the ideas immanent in nervous activity. *Bulletin of Mathematical Biophysics*, (5): 115–137.

John. McCarthy, (1988). *IEEE Annals of the History of Computing* , **10**:227.

Mitchel, B.F., Dem'yanov, V.V. and Malozemov, V.N. (1971). Finding the point closest to the origin of the polyhedron. *Vestnik LGU* , (19):38-45.

Mitchel, B.F., Dem'yanov, V.V. and Malozemov, V.N. (1974). Finding the point of a polyhedron closest to the origin. *SIAM J Control*, **12**(1):19–26.

A. Newell, (1983). Intellectual Issues in the History of Artificial Intelligence. *The Study of Information: Interdisciplinary Messages, Wiley*.

Penev, G.D., Yakubovich, , V.A. (1971). About some tasks of adaptive behavior. *Dokl. AN SSSR*, **198**(4):787-790.

Polyak, B.T., (1964). Some methods of speeding up the convergence of iteration methods. *USSR Computational Mathematics and Mathematical Physics*, **4**(5): 1-17.

Polyak, B.T. and A.B. Juditsky, (1992). Acceleration of stochastic approximation by averaging. *SIAM Journal on Control and Optimization*, **30**(4): 838-855.

Pospelov D. A., (1998). Occurrence of Informatics in Russia. *In: Essays on the history of informatics in Russia" . Compiled by D.A.Pospelov, Ya.I. Fet* .

B. Recht, (2019). A Tour of Reinforcement Learning: The View from Continuous Control. *Annu. Rev. Control Robot. Auton. Syst*, (2): 253-279.

Sutton, R.S., Barto, A.G. and Williams R.J. (1992). Reinforcement learning is direct adaptive optimal control. *IEEE Control Systems Magazine*, **12**(2): Cited by: (189).

Timofeev, A.V. (1978). Robots and artificial intelligence. *M.: Nauka* .

Timofeev, A.V. , Kharichev, V.V., Shmidt A.A. and Yakubovich, , V.A., (1971). One task of image recognition and description. *Biological, medical cybernetics and bionics. Kyiv: Izd-vo Nauchnogo soveta pon kibernetike I Instituta kibernetiki*.

Vapnik, V.N., Chervonenkis, A.Ya. (1964). About one class of perceptrons. *Avtomatikf I telemekhanika* , **25**(1):112-120.

V. N. Vapnik , (1973). Machines learnnig pattern recognition," in Pattern Recognition Learning Algorithms. *Sovetskoe Radio, Moscow*, 5-28.

N. Wiener, (1948). Cybernetics or Control and Communication in the animal and the machine. *The MIT Press*.

Yakubovich, V.A. (1963). . Machines learning pattern recognition. *In the book: ≪Metody vychislenij≫, Izd-vo LGU*, (2): 95-131.

Yakubovich, , V.A. (1968). About one task of self-learning appropriate behavior. *Avtomatika I telemekhanika*, **(**8):119-139.

Yakubovich, , V.A. (1970). About the organization of "brain" of one class of systems that develop appropriate behavior (solved and unsolved problems). *4th All-Union Conference on Neurocybernetics, Rostov University Publishing House*.

Yakubovich, , V.A., Timofeev, A.V. (1971). // Dokl. AN SSSR. *Upravlenie I informatsyonnyi protses v schyvoi prirode. M.: Nauka* , 111-113.

Yakubovich, V.A. (1976). Adaptive suboptimal control of a linear dynamic object in the presence of a delay in control. *Kibernetika*, (1).

Yakubovich, V.A. (2021). Machines learning pattern recognition. *Vestnik SPbU*, (4).

Yakubovich, , V.A. (1965). Some general theoretical principles of the construction of trainable identification systems.I. *Vychislitel"naya tekhnika I voprosy programmirovaniya, L.: Izd-vo LGU*, 3–71.

Yakubovich, , V.A. (1966). Recurrent finitely convergent algorithms for solving systems of inequalities. *Dokl. AN SSSR*, **166**(6):1308-1312.

Yakubovich, , V.A. (1968). Towards the theory of adaptive systems. *Dokl. AN SSSR*, **182**(3):518-522.

Yakubovich, , V.A. (1968). Adaptive systems with multistep goal conditions. *Dokl. AN SSSR*, **183**(2):303-306.

Yang, X., Liu, D., Wang, D. (2014). Reinforcement learning for adaptive optimal control of unknown continuous-time nonlinear systems with input constraints. *International Journal of Control*, **87**(3):553-566. Times Cited: (112).

Zypkin, Ya.Z. (1968). Adaptation and training in automatic systems. *M.: Nauka* .