LABORATORY OF MATHEMATICAL PROBLEMS IN NATURAL SCIENCES

DEPARTMENT OF DIFFERENTIAL EQUATIONS

FACULTY OF MATHEMATICS AND MECHANICS

MOSCOW STATE UNIVERSITY

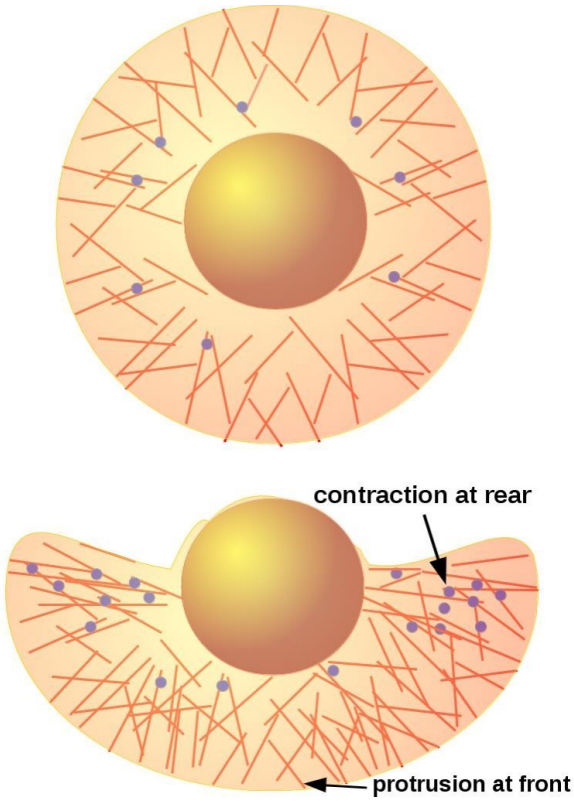
Laboratory of Mathematical Problems in Natural Sciences is a laboratory of industrial ("interdisciplinary") mathematics. It is a unit of Mechanics and Mathematics Faculty in Moscow State University.
Recently, a group of scientists from Differential Equations Department of Moscow State University, and Institute for Problems in Mechanics of Russian Academy of Sciences, took an active part in a number of applied research projects with Russian corporations “Uralchem” and “Uralkali”, University of Pennsylvania (USA), Scientific Technical Center “Kosmonit”, Public Corporation “Russian Space Systems”, as well as other industrial organizations. As a result of this collaboration, applied laboratory was created.

Mathematical biology

1. Chemotaxis

The ability of cells and cell ensembles in living organisms to move in a specific direction has long attracted attention of biologists, biochemists and biophysicists, as well as mathematicians, who create mathematical models of such motion. Examples are blood particles arriving to heal the wound in human skin, epithelial cells

moving collectively to regenerate damaged tissues, cells chasing intruders like enemy bacteria, etc. Somehow a cell or a group of cells decides where and when to move.
Cell motility is one of the most up-to-date and important problems of modern mathematical biology. Creating of appropriate mathematical models for this motion is actual problem in medicine and pharmacology.
Moreover, this field provides new and interesting problems in the theory of partial differential equations: existence of "traveling wave"-type solutions for parabolic equations and systems with nonlinear terms; well-posedness of boundary value problems for nonlinear parabolic and parabolic-elliptic systems with nonclassical boundary conditions: posed on an unknown boundary which moves in time, or nonlocal, linking boundary values at different points of the boundary.
Such problems are far from being studied yet, neither in regards of qualitative properties, nor in creating adequate numerical algorithms for solution and identifying parameters. We plan to continue our research from mathematical point of view.



2. Physics of Active Gels
Mathematical modeling of media with "active" elements is very interesting from both theoretical and practical points of view. For example, research of L.Berland proves that if a liquid contains bacteria able to react actively to situation, then the viscosity of this liquid changes dramatically (decreases several times!). First, this research was carried out by mathematical methods. Later, these works served as a basis for creation fluids with very low viscosity, using purely chemical methods (in the absence of any "living" elements). Now these liquids are used as ink for modern 3D printers. We consider this area to be extremely promising. Our group plans to continue this research, extending our interest to a wider range of media with active elements. These can be other continuous media (apart from classical liquids) with active elements others then bacteria.

Artificial Intelligence

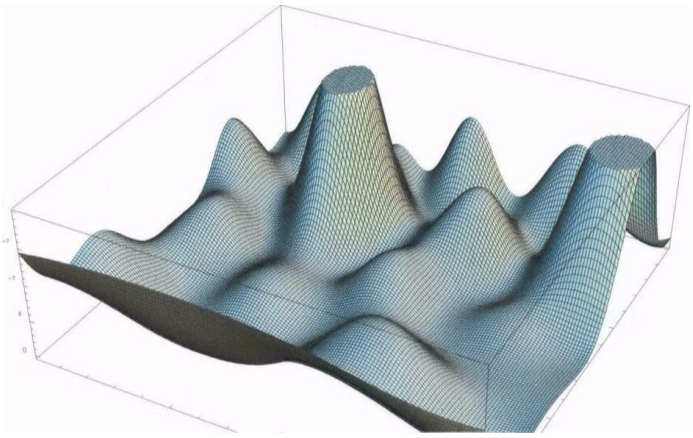
Mathematical models of different systems often contain parameters that cannot be obtained from “first principles”, they have “phenomenological” nature. However, these parameters can be determined by

configuring model parameters according to the results of experiments. This aim can be achieved using modern methods of artificial intelligence and electronic self-learning systems.
Various optimization methods play important role here, they help to find unknown parameters in our model. To do it, we must minimize the difference between certain sets of experimental and calculated data, which include the parameters to be identified.

Supercomputer "Lomonosov" installed in Moscow University in 2009

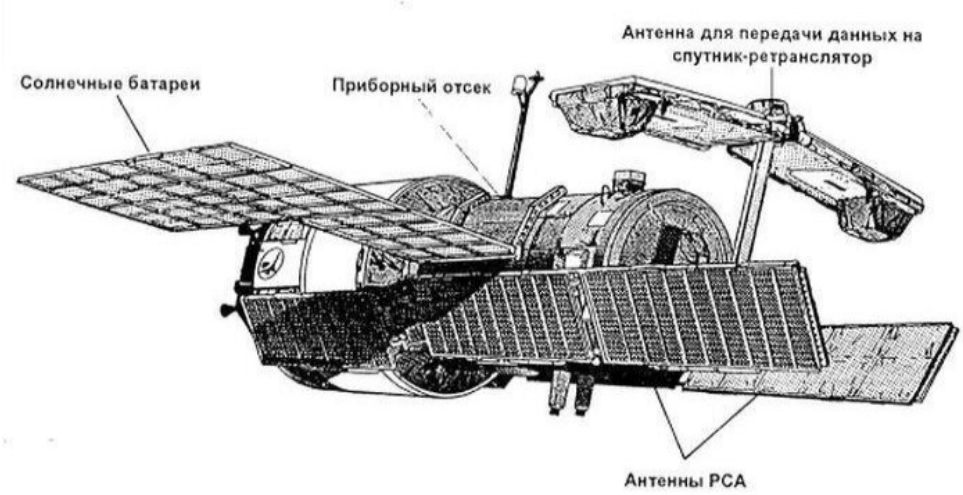
Inverse problems of electrodynamics

1. Holographic methods
Study of subwavelength capabilities of holographic methods. Reconstruction of the spatial structure of a molecule by holographic methods, comparing the interference picture of diverging electron beam on a molecule with a reference electron beam. Possible applications - synthesis of new medicaments.



2. Radiometric and radiolocation studies of the World Ocean
Problems of radiometric and radar study of the world ocean, in collaboration with Scientific Technical Center “Kosmonit” and Public Corporation “Russian Space Systems”. The main challenge is reconstructing the parameters of sea waves using the ocean's own radio emission and reflected radio signals. Computer simulation for own and reflected radio emission of the sea surface is carried out.

Active and passive space radiolocation



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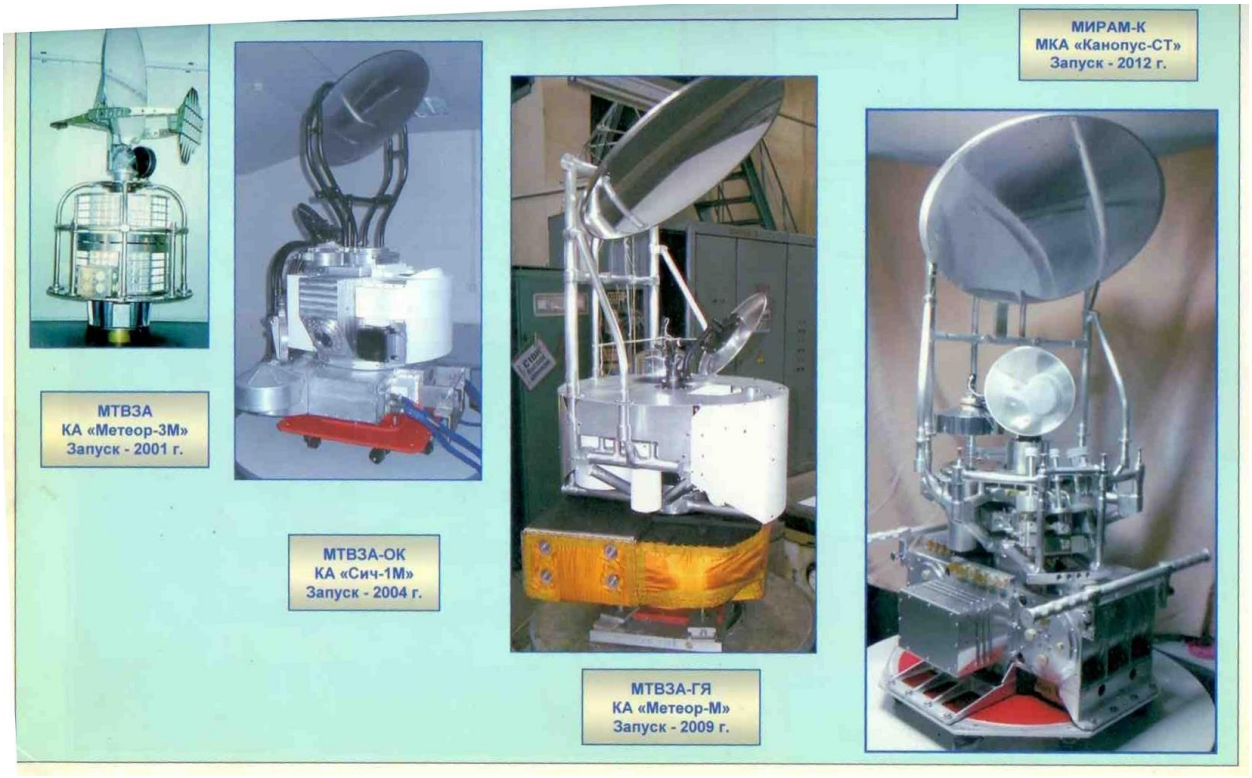
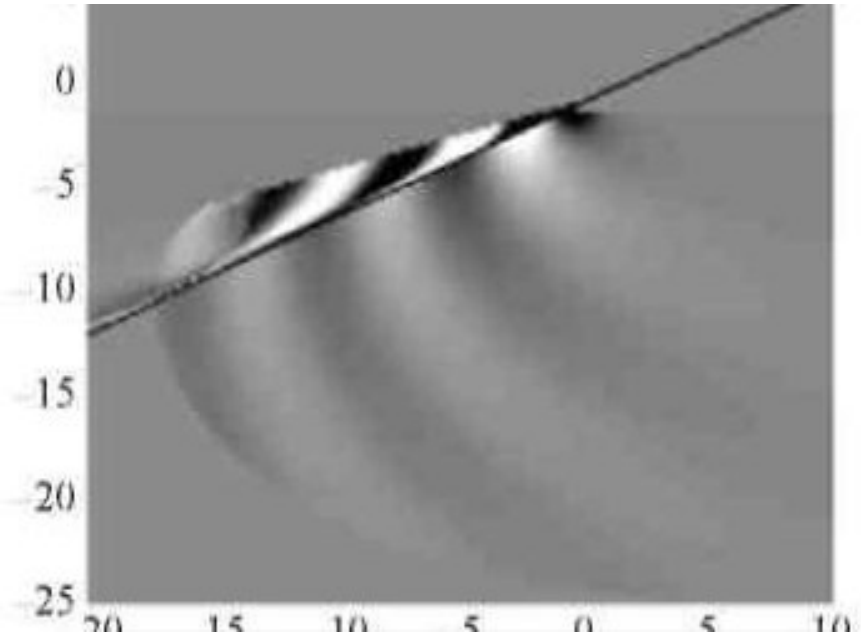
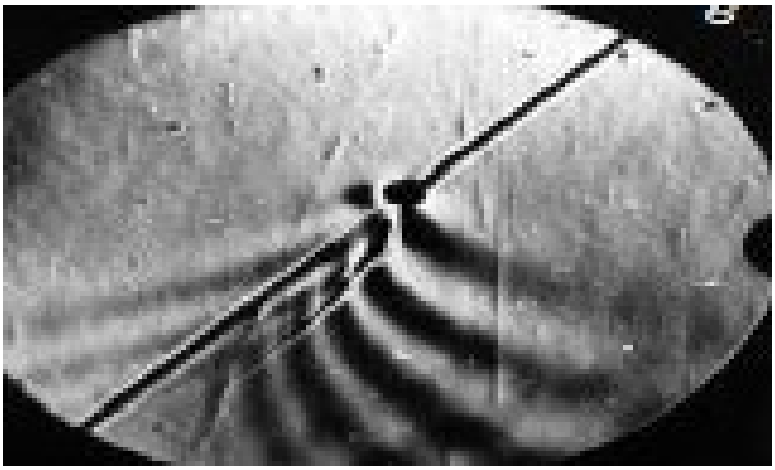


Radiometers

Internal waves in the ocean. Theory and experiment
The problem is to create an adequate model of waves caused by a moving object.



Result of mathematical modeling



Experiment Result

Mathematical Modeling of Mines

Joint projects with corporations "Uralchem" and "Uralkali" consider mathematical modeling of elastoplastic properties of salt formations, processes of creeping, plasticity and cracking in the salt mines of Perm region. Joint activities are related to the safety in potassium mines. Recently this topic became highly actual due to several accidents in salt mines near the town Bereznyaki. We plan to create mathematical model of potassium mines in Bereznyaki (Perm region) in order to predict the phenomena that may cause future accidents.
This project is named "virtual mine". We have already obtained analytical representations for effective characteristics of creeping processes in salt layers with clay inclusions.

Mine collapse in Solikamsk, September 2015

Layered salt formations (Bereznyaki)

Financial Mathematics

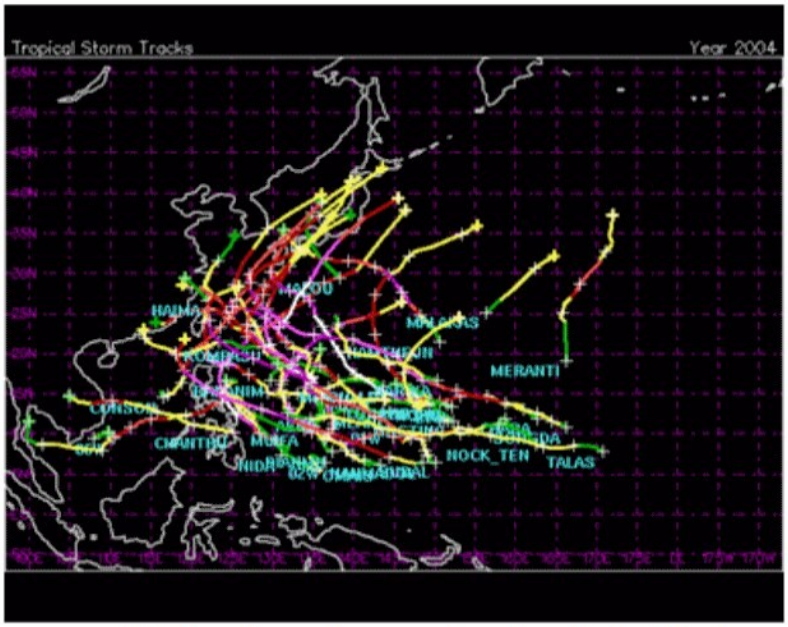
For almost twenty years seminar “Mathematical Models in Economics” is working at the Department of Differential Equations. This seminar is headed by professors O.S.Rozanova and A.S.Shamaev. Participants of this seminar include about 150 students of Mechanics and Mathematics Faculty, whose diploma works consider

mathematical models in economics. We are mostly interested in new and original boundary value problems for differential and integro-differential equations and systems that arise (and this is exactly the case!) in modern financial mathematics and economics.
For example, there are three Ph.D. theses of participants of our seminar - K.Khorev (Boundary value problems with unknown boundary related to the analysis of credit market), G.Kambarbaeva (Equations of Fokker-Plank type, arising in problem of managing an investment portfolio, whose actives are modeled by stochastic differential equations), A.Chechkin (Cauchy problems for parabolic equations with polynomial coefficients arising in actives management and hedging problems); also article of A.Asekov and A.Shamaev devoted to the construction of effective front in the actives management problem, where Fredholm theorems are applied for elliptic operators in unbounded domains. Interesting and new mathematical problems arise in creating actives models taking into account the psychology of market participants (O.S.Rozanova).
In our laboratory we plan to continue practical research in financial mathematics.

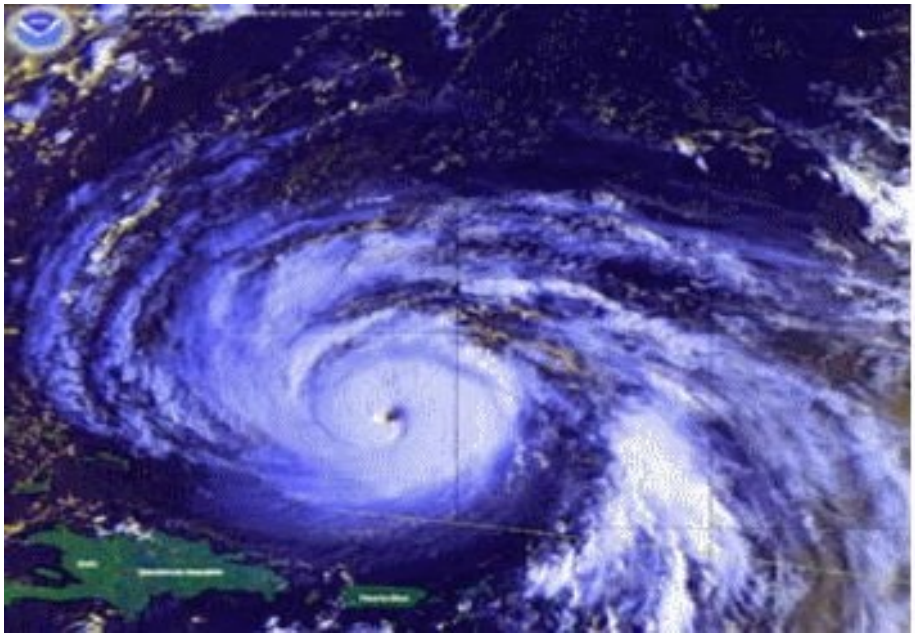
Atmosphere Dynamics

1. Study of large atmospheric vortices
Study of possible trajectories of long-lasting large-scale atmospheric vortices (typhoons or hurricanes), comparison with real trajectories. Study of their structure, conditions of their formation, stability in two-dimensional and three-dimensional models. Full model approximations. Study of topography influence on the trajectory of vortices. Collaboration with scientists from Taiwan, China, USA, France.

1. Rozanova, O.S., Turzynsky, M.K. (2018) Nonlinear stability of localized and non-localized vortices in rotating compressible media, Theory, Numerics and Applications of Hyperbolic Problems, Springer Proceedings in Mathematics & Statistics, v. 236, 567-580.
2. Rozanova, O.S., Turzynsky, M.K. (2018) On Systems of Nonlinear ODE Arising in Gas Dynamics: Application to Vortical Motion, Differential and Difference Equations with Applications. Springer Proceedings in Mathematics & Statistics, v. 230, 387-398.
3. Rozanova O.S. (2016) Frozen and almost frozen structures in the compressible rotating fluid Bulletin of the Brazilian Mathematical Society, 47, № 2, 715-726.
4. Rozanova Olga, Yu Jui-Ling, Hu Chin-Kun (2012) On the position of vortex in a two-dimensional model of atmosphere, Nonlinear Analysis: Real World Applications, 13, 1941-1954.
5. Rozanova Olga S., Yu Jui-Ling, Hu Chin-Kun (2010) Typhoon eye trajectory based on a mathematical model: comparing with observational data, Nonlinear Analysis: Real World Applications, 11, № 3, 1847-1861.



http://weather.unisys.com/hurricane/index.html1



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LIST OF PUBLICATIONS PREPARED AS PART OF THE PROJECT for 2020.

1. О.С.Розанова, С.И.Никулин, О некоторых аналитически решаемых задачах теории игр среднего поля, Вестник МГУ. Сер.1. Математика.Механика. №4, 2020.
2. Olga S. Rozanova, Singularity formation for rotational gas dynamics, Journal of Mathematical Analysis and Applications, Volume 492, Issue 1, 2020 (**Q1**).
3. Bratus A., Drozhzhin S., Yakushkina T. (2019) Evolutionary Adaptation of Permanent Replicator System. *In the book "Trends in Biomathematics, Modelling Cells, Flows, Epidemics and Environment"*, Springer, ISBN978-3-030-46306-9.
4. Ivan Yegorov, Artem S. Novozhilov and Alexander S. Bratus. Open quasicpecies models: optimization, and distributed extension. *Journal of Mathematics and Application* (2019). https://doi.org/10/1016/j.jmaa.219.123477
5. Bratus A., Drozhzhin S., Yakushkina T. (2020) Fitness Optimization and Evolution of Permanent Replicator Systems. *Journal of Mathematical Biology* (accepted for publication (**Q1**).
6. T. N. Bobyleva, A. S. Shamaev. Mathematical Model of a Filter for Water Treatment Using Biofilms (Scopus).

Publications for 2021 with brief comments

1..Rozanova, O.S., Chizhonkov E.V. On the conditions for the breaking of oscillations in a cold plasma.. // Z. Angew. Math. Phys. 72, 13. 2021 **(SCOPUS Q1).**

The Cauchy problem for a quasilinear system of hyperbolic equations describing plane one-dimensional relativistic oscillations of electrons in a cold plasma is considered. For some simplified statement of the problem, a criterion for the existence of a solution global in time is obtained. For the original problem, a sufficient condition for the loss of smoothness is found, as well as a sufficient condition for the solution to remain smooth for at least one oscillation period. In addition, it is shown that, in the general case, arbitrarily small perturbations of a trivial state lead to the formation of singularities in a finite time. It is further proved that there are special initial data such that the corresponding solution remains smooth all the time, even in the relativistic case. Nevertheless, an arbitrary small perturbation of a general form destroys these smooth solutions global in time. The nature of the solution singularities is illustrated by numerical examples.

2.Romanov I.V.,· Shamaev A.S. Exact Bounded Boundary Controllability to Rest for the Two-Dimensional Wave Equation, вышла в Journal of Optimization Theory and Applications, 188(3), 925-938, 2021 (**SCOPUS Q1)**

The paper proves the possibility of bringing the vibrations of the membrane to complete rest with the help of control actions applied to the boundary of the membrane. At the same time, a control method is developed that makes it possible to bring the oscillatory system to rest with the help of small absolute value of control actions, as well as in the presence of restrictions for the control action on its derivatives both in space variables and in time. This is an important feature of this work, since real control systems always have similar restrictions on the control action and on the nature of the modes of its change. For the first time, a control method is proposed under such restrictions on the control action.

3. Sergei Drozhzhin, Tatiana Yakushiкina, Alexander S. Bratus. Fitness optimization and evolution of permanent replicator systems. **Journal of Mathematical Biology** (2021) 82:15, https://doi.org/10.1007/s00285-021-01548-8, **WOS, SKOPUS Q1**.

The article is devoted to the problem of evolutionary adaptation of systems of complex macromolecules. This article proposes a new mathematical model for the evolution of biological communities based on the hypothesis of a fast time of active system dynamics and a slow time of adaptation. As an example, the results of evolutionary adaptation of the system of catalysis of RNA macromolecules are given. It is shown that as a result of evolutionary change, the system acquires the property of resistance to parasitic macromolecules, from the impact of which this system died before the moment of evolutionary change.

4. Bobyleva T.N, Shamaev A.S. Mathematical Model of a Filter for Water Treatment Using Biofilms,IOP Conf. Series: Materials Science and Engineering 1079 (2021) 032081 IOP Publishing doi:10.1088/1757-899X/1079/3/032081

The paper builds a mathematical model of water purification using a biologically active filter. The filter is a set of polymer cubes placed in a cylindrical vessel. Each cube is pressed from thin polymer rods. On the surface of each such rod, a biologically active film with bacteria is formed, which absorb harmful impurities in the water flowing over the surface of the rod. The article builds a model for the absorption of harmful impurities in water in a full vessel. Its mathematical implementation is reduced to solving a large number (millions) of ordinary differential equations, each of which is responsible for the absorption of harmful impurities by bacteria on one of the mentioned rods (impurities for bacteria - food). In general, the model can be effectively used to optimize the design parameters of the filter. The work was carried out in contact with employees of the Department of Water Supply, Sewerage and Water Treatment of the Moscow Construction University.

5. Rozanova O.S., Manapov I. Mean field game equations with underlying jump-diffusion process, AIP Conference Proceedings, 2512(2021), № 1, в печати (ArXiv e-prints, № arXiv:2108.00244)

It is known that many phenomena in nature and society, in particular, the change in the price of a market asset, can be well described by the processes of abrupt diffusion. These processes combine random walk and jumps. The theory of mean field games describes the behavior of a large number of agents pursuing individual goals under stochastic optimal control. The conclusions of this theory fundamentally depend on what properties the random process present in the model has. In this paper, we generalize the previously obtained results to the case of abrupt diffusion and, in particular, show how the investor's opinion about the value of an asset changes in response to the control method.

6. Rozanova O.S., Uspenskaya O.V. On Properties of Solutions of the Cauchy Problem for Two-Dimensional Transport Equations on a Rotating Plane,
Moscow University Mathematics Bulletin, 76(2021), № 1, с. 1-8 (SCOPUS Q3)

The behavior of solutions of hyperbolic equations in the case when the spatial dimension of the problem is greater than one is extremely complicated. Exact solutions can be found extremely rarely, and the nature of the resulting singularities is unclear. In this paper, we study a system of transport equations in a plane in the presence of a constant Coriolis force,

for which we managed to advance in the study of solutions, and even develop an algorithm that allows us to find the time and place of the emerging singularity. It turned out that the presence of the Coriolis force can eliminate the formation of singularities.

7. Rozanova O. S., Chizhonkov E. V. Stabilization and blow-up in the relativistic model of cold collisional plasma, Zeitschrift für angewandte Mathematik und Physik, в печати (ArXiv e-prints 2103.11685), (SCOPUS Q1)

The complete system of equations describing cold plasma with collisions taken into account is very complicated. Due to the fact that solutions lose their smoothness over a finite time, even a numerical solution using a supercomputer cannot be reliable. In order to theoretically describe the features of the solution, physicists usually linearize the problem, losing many important features in the process. In this paper, we act differently: we single out subclasses of solutions that satisfy the original nonlinear system of equations and study their properties. In this way, it is possible, in particular, to divide the solutions into those that stabilize to zero and those that lose their smoothness in a finite time.

8. 6. A.S. Bratus, M.C. Litzinger, Y. Todorov, M. Foller-Nord, M. Chaudhary. On optimal therapy protocols in the mathematical model of prostate cancer progression. **Advanced System Science Application,** 04; 83-104, 2021, (1.0), **SKOPUS Q3.**

The article is devoted to the actual problem of finding the optimal therapy for prostate cancer, which is one of the most common forms of cancer in men. The mathematical model is based on modern data from medical studies of this disease. An optimal strategy for the use of chemotherapeutic drugs is proposed, taking into account their negative impact on healthy cells and cells of the immune system. The results of this study were introduced to the doctors of the Research Institute of Urology and Interventional Radiology named after. N. A. Lopatkina (Moscow).

9. **Quasispecies Systems: New Approach to Evolutionary Adaptation. Chinese Journal of Physics (2021), (Q2), принята к публикации, (Igor Samokhin, Tatiana Yakushkina, Alexander S. Bratus**)

The article is devoted to the mathematical model of the evolutionary change of the biological community of species, one of which is subjected to targeted destruction. This situation is typical in the case when a certain type of cancer cells and pathogenic bacteria are purposefully destroyed with the help of drugs. The constructed mathematical model makes it possible to predict the process, as a result of which there is a change of priorities, and in the process of mutation and adaptation of the fitness landscape, other species gain

an advantage in development.

RELEASED PUBLICATIONS 2021

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10. Bobyleva T.N, Shamaev A.S. Mathematical Model of a Filter for Water Treatment Using Biofilms**,** IOP Conf. Series: Materials Science and Engineering 1079 (2021) 032081 IOP Publishing doi:10.1088/1757-899X/1079/3/032081

11. *Байдулов В.Г. (Baydulov V.G.)* О решении обратной задачи движения источника в стратифицированной жидкости ООО ИСПО принт, Волны и вихри в сложных средах: 12-ая международная конференция – школа молодых ученых; 01 – 03 декабря 2021 г., Москва: Сборник материалов школы (2021 г.) РИНЦ

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19. *Романов И.В. (Romanov I.V.)* **Исследование управляемости для некоторых систем, описываемых интегро-дифференциальными уравнениями** Известия РАН. Теория и системы управления (2022 г.) WOS SCOPUS РИНЦ

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13. V Международная конференция «Суперкомпьютерные технологии математического моделирования» 7.06.2022–30.06.2022, г. Москва, Россия, http://multiscalemr.ru/ru/sctemm_2022/
Байдулов В.Г., Князьков Д.Ю., Савин А.С., Шамаев А.С. Прямые и обратные задачи динамики поверхности жидкости под действием течений (устное выступление)

14. 20th International Conference of Numerical Analysis and Applied Mathematics 19.09.2022–25.092022, Heraklion, Crete, Greece, http://history.icnaam.org/icnaam_2022/ICNAAM%202022/icnaam.org/index.html
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15. 10th International Conference on Wave Mechanics and Vibrations, Lisbon, Portugal, July 4-6, 2022, https://www.wmvc2022.org/
Gavrikov A., Kostin G. Optimal LQR control for longitudinal vibrations of an elastic rod actuated by distributed and boundary inputs (устное выступление)

16. XVI Международная конференция «Устойчивость и колебания нелинейных систем управления» (конференция Пятницкого), Москва, Россия, 1–3 июня 2022, https://stab22.ipu.ru
Kostin G. Optimization of thermodynamic processes in heat-conducting rods controlled by a Peltier element (устное выступление)

17. XVI Международная конференция «Устойчивость и колебания нелинейных систем управления» (конференция Пятницкого), Москва, Россия, 1–3 июня 2022, https://stab22.ipu.ru
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18. 18th IFAC Workshop on Control Applications of Optimization, July 18-22, 2022, Gif sur Yvette, Франция, 18-22 июля 2022, https://cao2022.sciencesconf.org/

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19.Романов И.В. Исследование управляемости для некоторой динамической системы с распределенными параметрами, описываемой интегро-дифференциальным уравнением. Изв. РАН, ТиСУ. 2022, №2, стр. 58-61. (Q2 по версии Scopus для переводной версии журнала)

20..Романов И.В., Шамаев А.С. Точное управление распределенной системой, описываемой волновым уравнением с интегральной памятью. Проблемы математического анализа. 2022, Вып. 115, стр. 3-13.

21. Romanov I., Shamaev A. Exact Controllability of the Distributed System Governedby the Wave Equation with Memory. Proceedings of FORM 2022. V. 282.2023.

22. Романов И.В., Шамаев А.С. Об отсутствии управляемости в моделях “наивной механики”. Три исключительных случая. (Принято к публикации в журнале Прикладная математика и механика).

Acepted papers

23. И.В.Романов, А.С.Шамаев. Управляемость в покой для уравнения колебаний пластинки на торе в случае локального силового воздействия. Мат. Заметки, Q2.

19 articles from q1,q2 from 48 SCOPUS articles, 13 from q1

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Foreign director and co-founder of the Laboratory
Honorary Professor of Moscow State University, Professor of Pennsylvania State University
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- Rozanova O.S.- professor
- Gavrikov A.A. - senior researcher
- Knyazkov D.Yu. - senior researcher
- Kapustina T.O. – associate professor
- Chernik V.V. - researcher
- Romanov M.S.- associate professor
- Turtsynsky M.K. – senior lecturer
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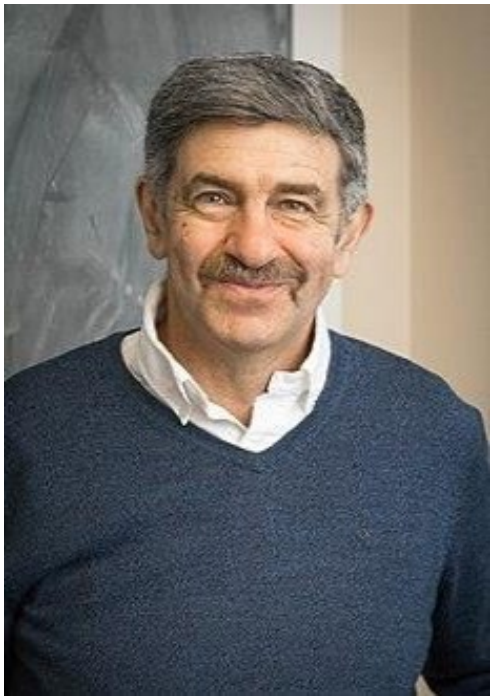

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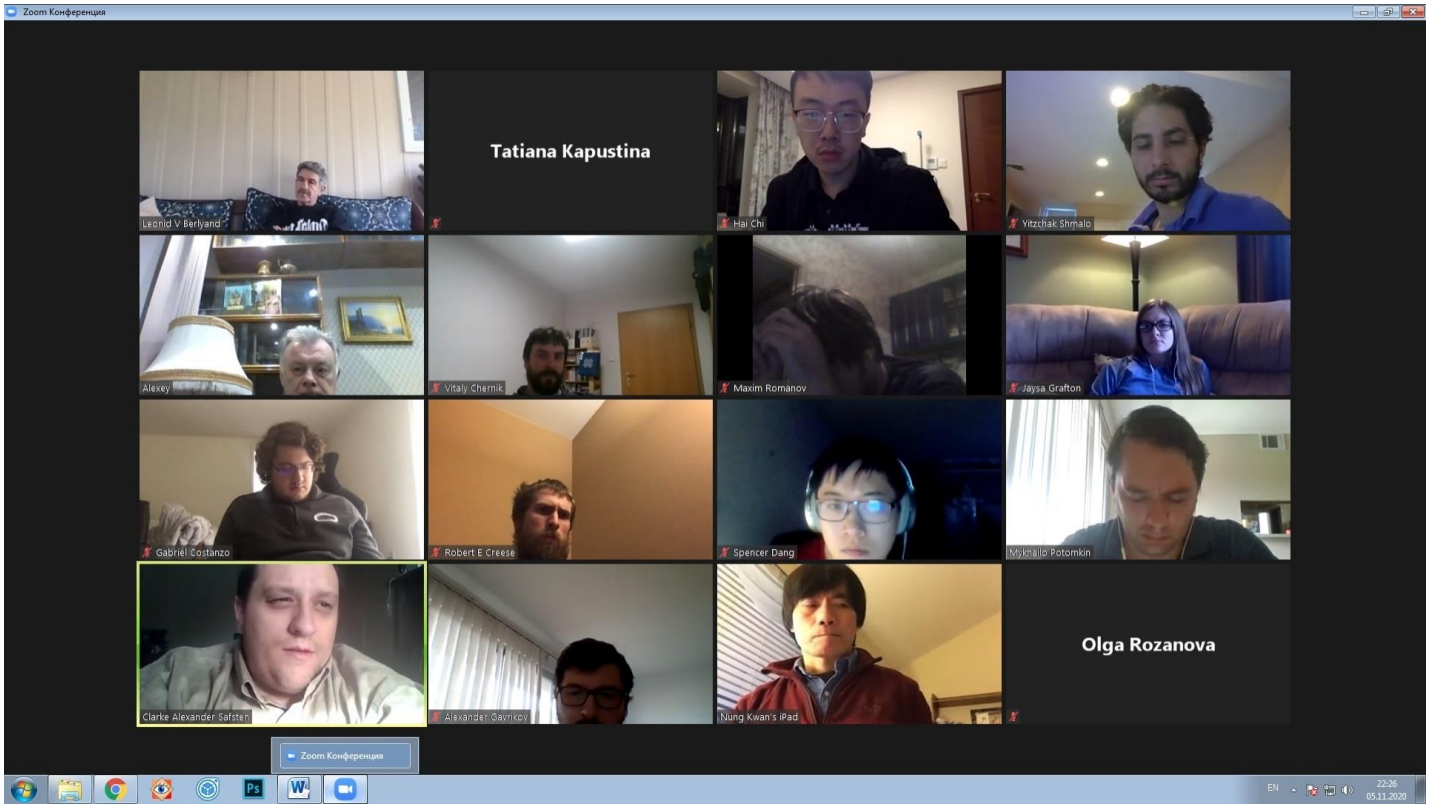
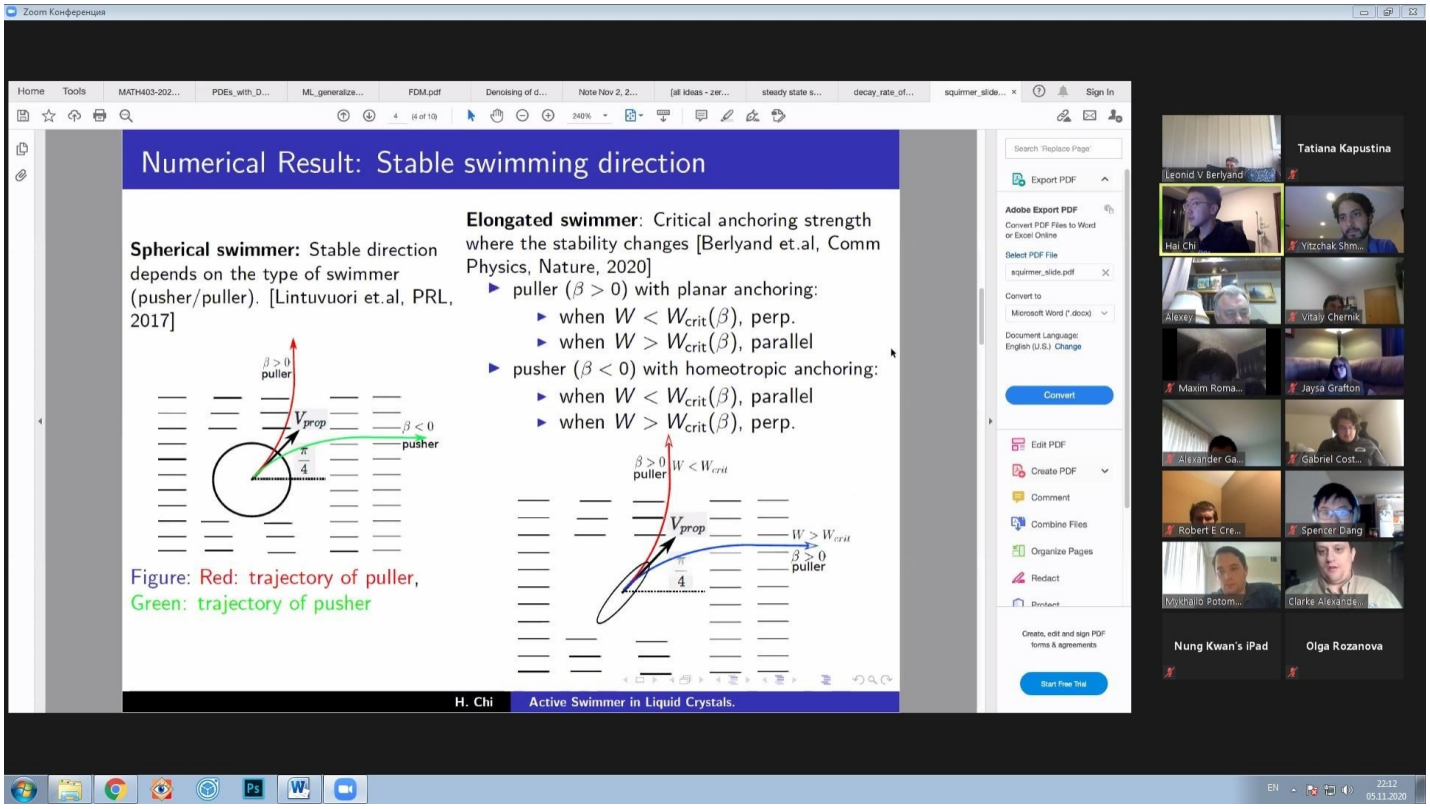
Senior Researcher D.Yu.Knyazkov

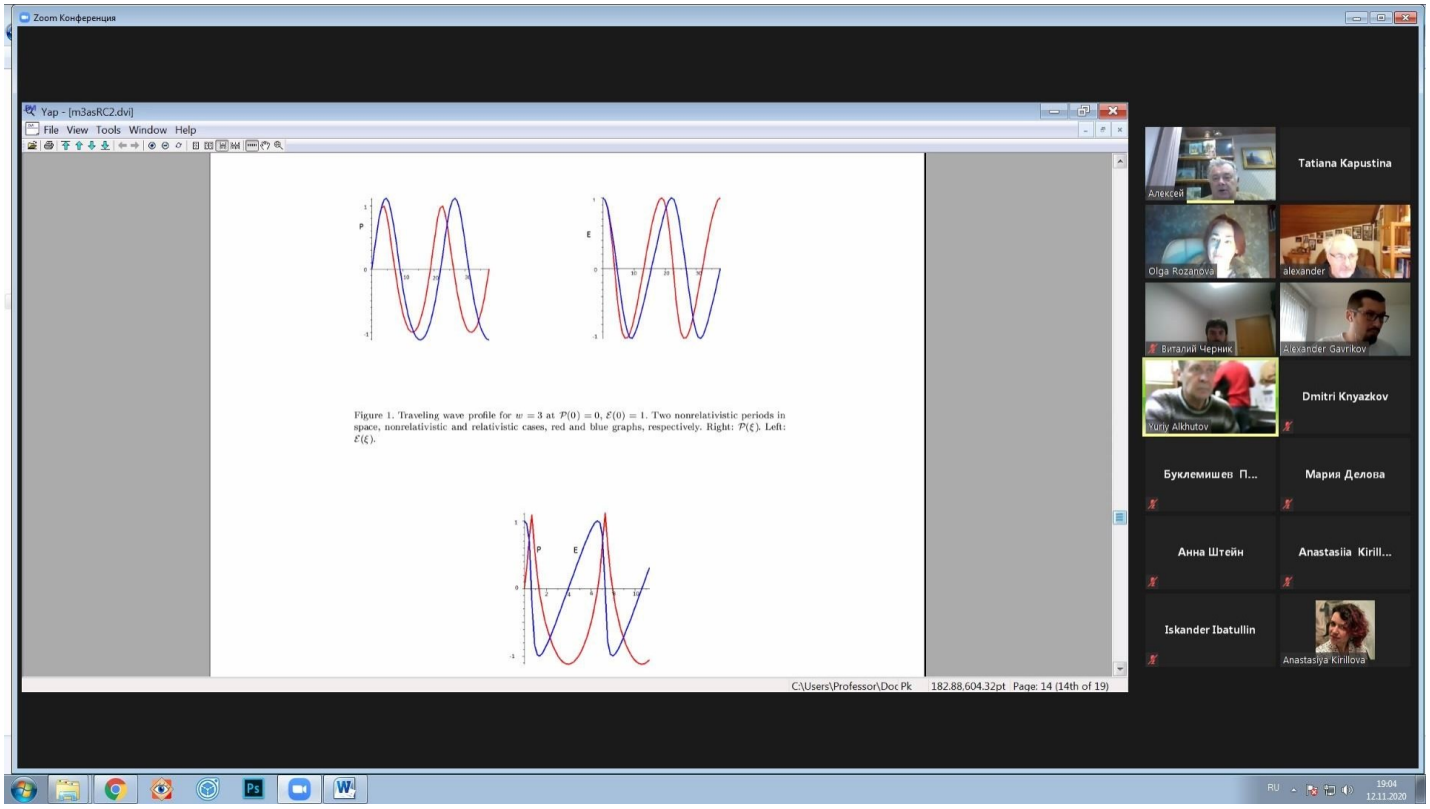
Senior Lecturer M.K.Turtsinsky

Laboratory Seminar



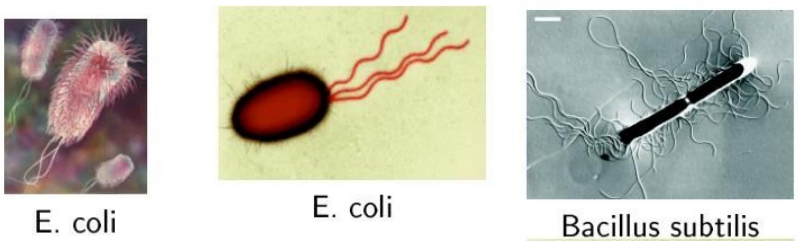


Discussion at joint Russian-American seminar concerning mathematical model of bacteria motion in viscous fluid with complex rheology, which simulates a mucous membrane. The problem is to create mathematical model explaining a number of experimentally observed phenomena in bacteria motion in viscous liquid with complex rheology: the choice of bacteria orientation during movement, mutual influence of bacteria, etc.

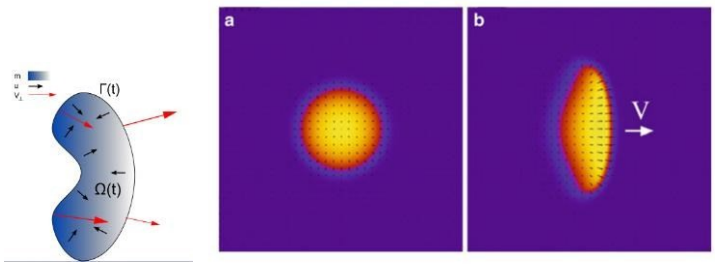


Second line - O.Rozanova and A.Bratus, third line - V.Chernik and A.Gavrikov.

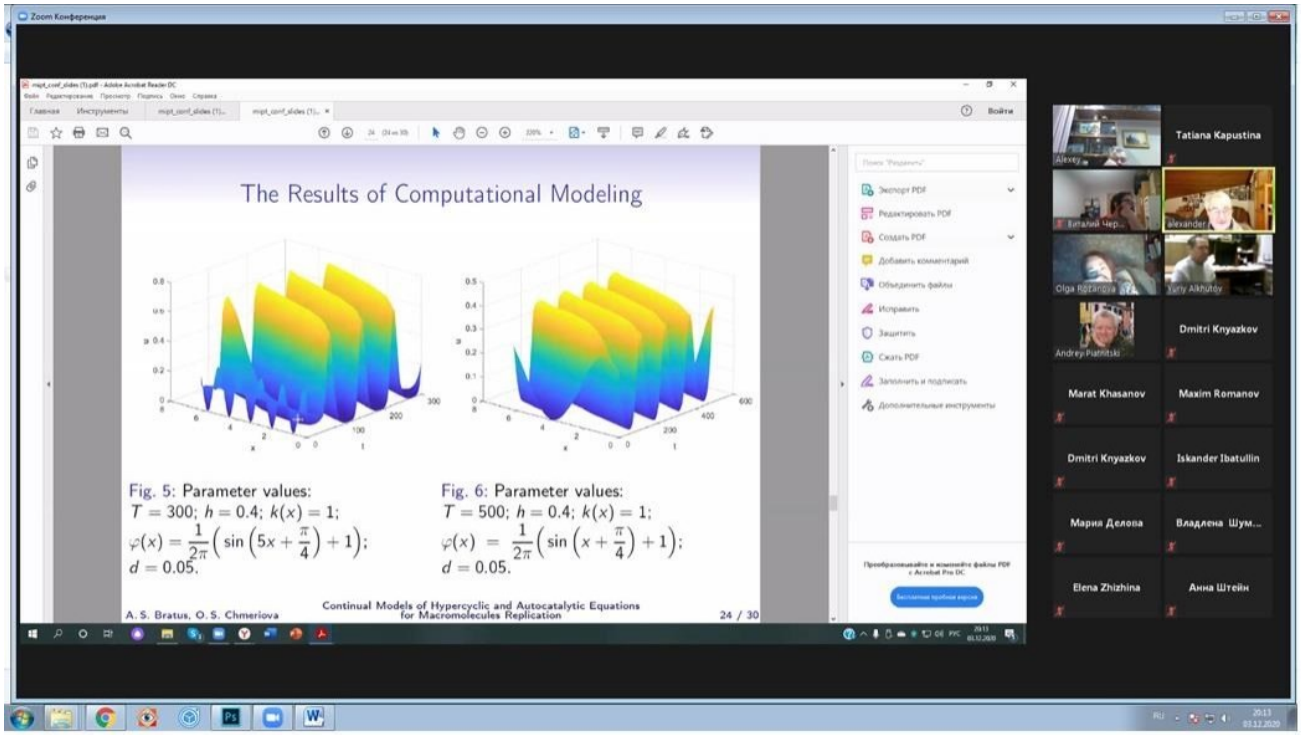
Using appropriate mathematical model of bacteria motion, it would be possible to give recommendations about control of bacteria concentration for medical purposes.

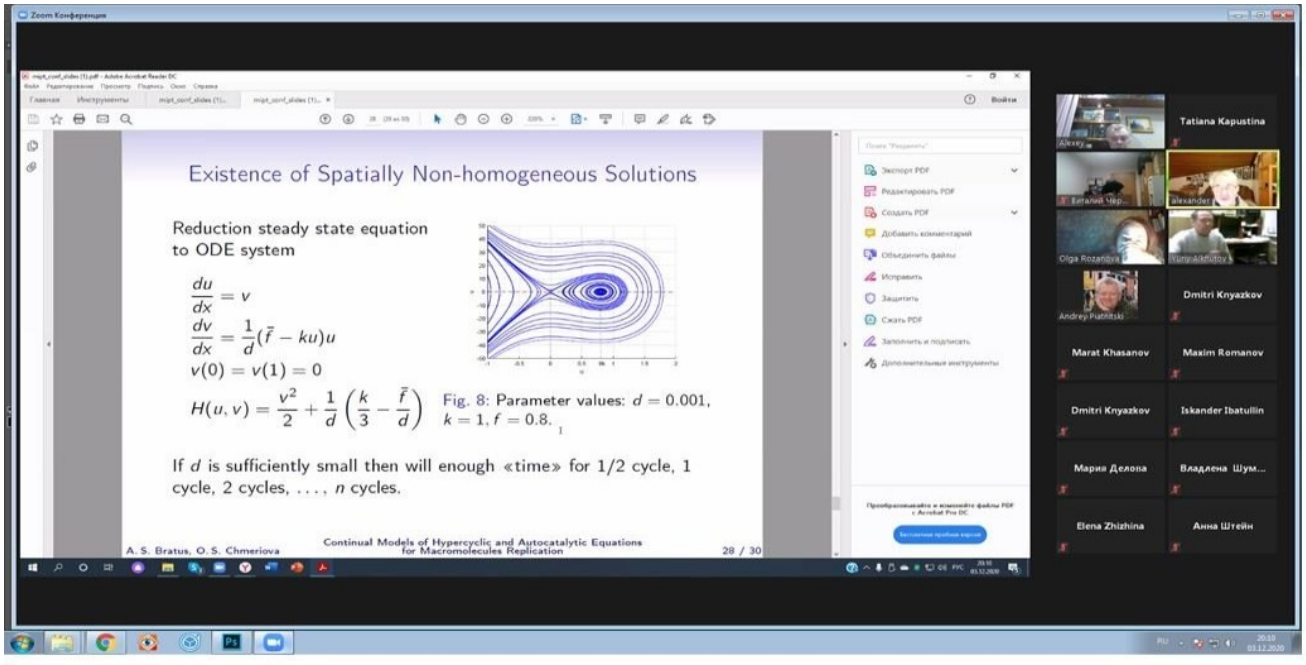


Various types of bacteria. Active elements are visible, which bacteria use to move in liquid medium. Mathematical model should consider bacteria structure.

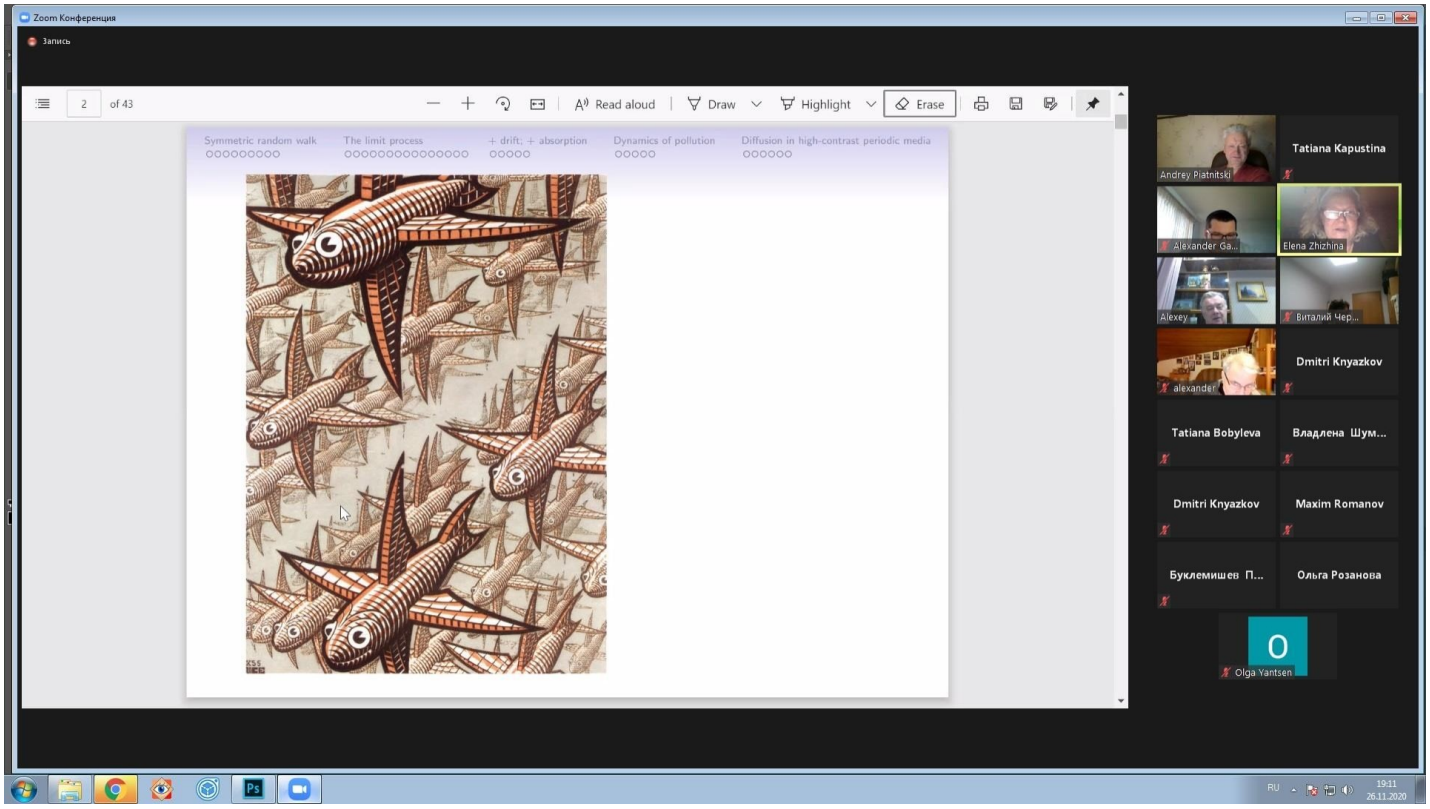


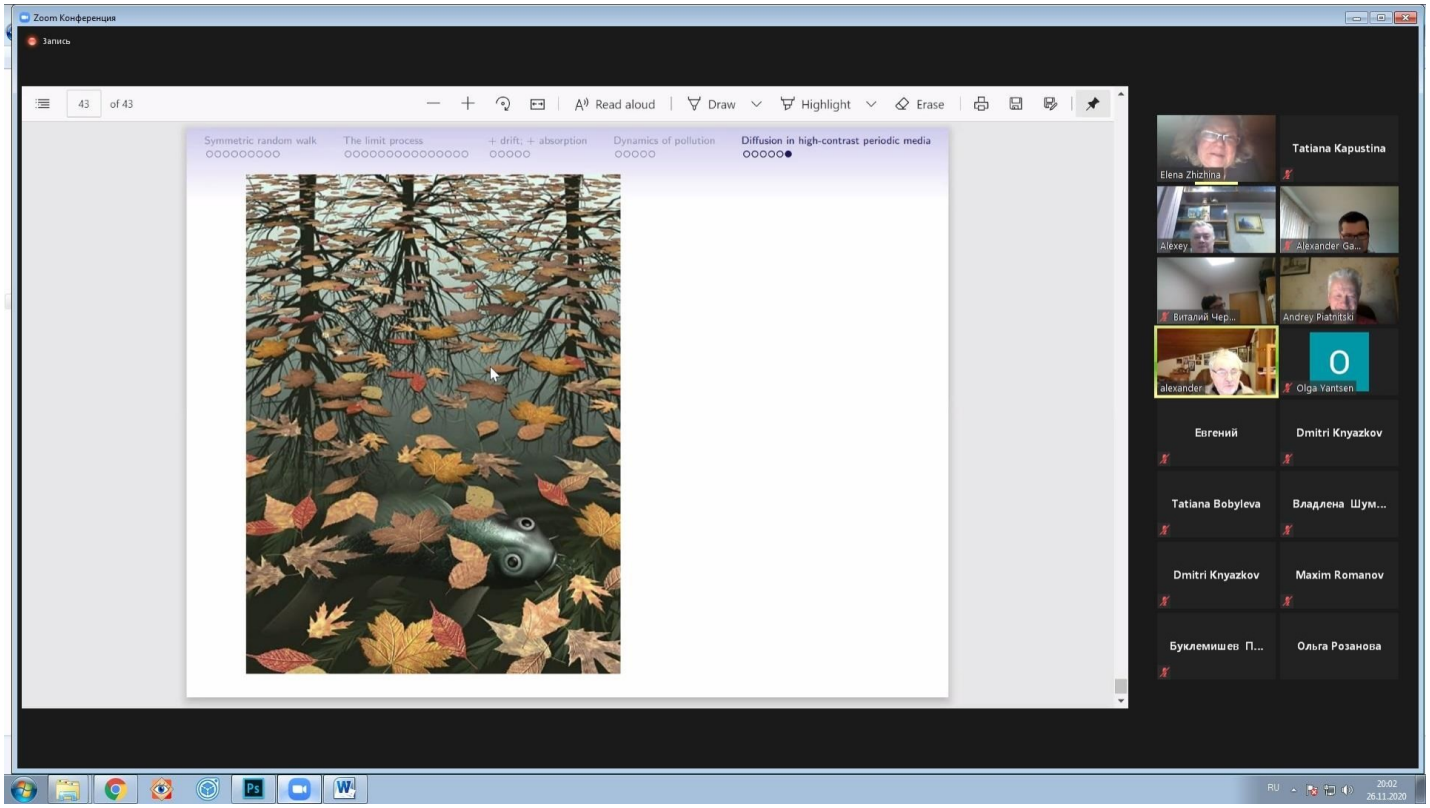
Mathematical modeling of cell motion (phenomenon of "chemotaxis"). When the cell shape or chemical environment is disturbed, the cell begins to move – how to explain it? We are searching for adequate mathematical model.





Discussion at a joint Russian-American seminar: problems concerning stability of hypercyclic replication. This mathematical model is used to simulate the processes of "prebiological" evolution.





Discussion of questions related to biological technologies for water purification. Active films inside the filter contain bacteria which absorb contaminants and hence purify water.