Research Statement of A. Chervanyov

I am a soft-matter theorist who extensively employs methods of statistical physics, both analytical and numerical, to quantitatively understand a wide range of practically relevant soft-matter systems, ranging from active matter to polymer nanocomposites. Earlier in my career, I worked on the non-equilibrium hydrodynamics of superfluid mixtures and on the kinetic properties of quasiparticle mixtures (e.g. electrons and phonons in semiconductors, as well as phonons, rotons, and impuritons in superfluid helium solutions), with the aim of understanding the formation of steady non-equilibrium states in these systems.

The physical systems investigated in my current research include:

- polymer nanocomposites (polymer solutions, melts, and rubbers containing nanofillers);
- effects of fillers (carbon nanotubes, carbon black) on the thermodynamic, mechanical and electrical properties of polymer nanocomposites;
- effects of nanoparticles on the compatibilization of polymer blends and other hybrid polymer systems.
- pattern formation in systems of self-propelled nano- and microparticles;
- polymer-mediated interactions between nanoparticles;
- physical adsorption of polymers;

My theoretical toolbox includes:

- self-consistent field theory;
- static and dynamic density functional theory;
- phase-field modeling;
- integral equation methods in liquid-state theory (e.g. PRISM);
- kinetic equations;
- cumulant and incremental expansion techniques.

Computer skills: Python, C++, Mathematica; frameworks and libraries: FEM PETSc, petIGA, SIMPATICO.

The detailed account of my **research accomplishments** is given below, ordered by their relevance to my current work.

Most Important Research Accomplishments (Chronological order)

- **Conductivity of filled diblock copolymers.** By combining a phase-field model describing the morphology of diblock copolymer systems (DBC) with Monte Carlo simulations and a resistor network model for the electrical properties of the filler network, I calculate the conductivity of diblock-copolymer-based composites. The analysis demonstrates that insulating diblock copolymers filled with conductive particles (e.g. carbon nanotubes or carbon black) can act as electrically responsive soft composites whose conductivity changes in response to external stimuli-induced morphological transitions. In particular, the order-disorder transition of the host DBC is found to cause a conductor-insulator transition in the filler network. The order–order transition between cylindrical and lamellar morphologies of the diblock copolymer induces a pronounced spike in the composite conductivity. The strong correlation between the morphology of the polymer host system and its electrical response can be exploited in electrical sensing applications, highlighting the practical relevance of the present research.

- **Phase-field modeling of pattern formation in active matter.** Using phase-field approaches, I investigate the emergence of moving and resting patterns in systems of self-propelled particles as a function of orientational correlations, thermal entropy, and the magnitude of active driving forces. The interplay of these effects results in a rich variety of crystalline states that provide promising routes toward the design of novel active materials.

- **Non-monotonic conductivity of CNT-filled elastomers under uniaxial deformation.** In close collaboration with experimental colleagues, we explained the experimentally observed non-monotonic dependence of electrical conductivity on applied uniaxial stress in carbon-nanotube-filled elastomers. The theoretical model is based on a combination of percolation theory and nonlinear elasticity models. The resulting predictions show excellent agreement with experimental data and demonstrate the potential of such composites as piezoresistive soft sensors.

- **Polymer-mediated effective interactions between fillers in polymer blends.** I predicted a novel mechanism of polymer-mediated interactions between fillers in polymer blends that originates from filler-induced variations in the local blend composition. These compositional correlations extend over significantly larger length scales than conventional density correlations responsible for osmotic depletion forces and therefore dominate the interaction mechanism in dense polymer blends used in practical applications.

- **Potential theory of polymer-mediated interactions in colloid–polymer mixtures.** By developing a potential theory for polymer-mediated interactions between spherical colloids, I investigated many-body effects on depletion forces in colloid-polymer mixtures and obtained effective many-body depletion potentials consistent with simulations and experiments.

- **Polymer-mediated coagulation-fragmentation of colloids under shear.** I developed a self-consistent mean-rate approach that allows analytical solutions of coagulation-fragmentation balance equations under mass conservation constraints. Combining this approach with liquid-state theory, I derived stability ratios and coagulation rates in colloidal systems with adsorbing and non-adsorbing polymers.

- **Adsorption of polymers on chemically patterned surfaces.** I performed a comparative theoretical analysis of polymer adsorption on regularly and randomly patterned substrates using self-consistent perturbation theory and transfer-operator methods, identifying universal trends governing adsorption on chemically heterogeneous surfaces.

- **Ordered surface structures from PNIPAM-based microgels.** In close collaboration with experimental groups, I studied the self-assembly of PNIPAM-based microgels on surfaces and demonstrated that the interplay of capillary attraction and steric repulsion leads to stable, loosely packed two-dimensional microgel arrays.

- **Interactions between polymer brushes in supercritical and organic fluids.** I constructed a two-order-parameter self-consistent effective field theory describing interactions between polymer brushes immersed in solvents with complex thermodynamic properties, successfully explaining experimental observations in dense and supercritical fluids.

- **Reduced kinetic models for quasiparticle transport in confined geometries.** I extended the Bhatnagar-Gross-Krook collision model to multicomponent quasiparticle mixtures, enabling the description of mutual drag effects and quantum corrections to the Knudsen effect in confined superfluid systems.
- **Incremental expansion methods for strongly correlated systems.** I developed a diagrammatic incremental expansion formalism for calculating thermodynamic properties of dense classical systems, providing an alternative to traditional virial expansions.
- **Non-equilibrium stationary states of superfluid helium isotope mixtures.** As part of my doctoral research, I studied non-equilibrium stationary states in superfluid helium isotope mixtures, including quantum transport phenomena, equations of state, and the role of phonon and roton excitations in transport coefficients.