Winter School on Driven Amorphous Materials
November 20-25, 2022
The David Lopatie Conference Centre
Weizmann Institute of Science

FOR1394

BIO-INSPIRED MATERIALS
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The Maurice and Gabriela Goldschleger Conference Foundation at the Weizmann Institute of Science

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Program & abstracts

Time	Sunday 20	Monday 21	Tuesday 22	Wednesday 23	Thursday 24	Friday 25
08:45–9:00		I. Procaccia		08:00 Excursion		Free day
09:00–10:00		E. Sharon	M. Fuchs		E. Bouchbinder	
10:00–11:00		J. Dyre	G. Tarjus		F. Scheffold	
11:00–11:30		Coffee break	Coffee break		Coffee break	
11:30–12:30		M. Ciamarra	J. Fineberg		11:30 F. Vogel 11:45 D. Shohat 12:00 N. Livne 12:15 C. Sirote	
12:30–14:00		Lunch	Lunch		Lunch	
14:00–15:00		E. Lerner	A. Zippelius		Y. Lahini	
15:00–16:00		M. Moshe	Y. Shokef		E. Agoritsa	
16:00–16:30			16:00 A. Moriel 16:15 D. Richard		T. Voigtmann	
17:00–19:00	Welcome Reception					

Contents

Message from the Prof. Itamar Procaccia

Message from the Prof. Thomas Franosch

Message from the Prof. Thomas Voigtmann

Introduction

Amorphous solids span a wide array of materials, from granular (like sand), glassy (like silica or metallic glasses, to soft materials like colloids. Amorphous materials are ubiquitous in applications, and understanding their macroscopic properties is a major aim for materials science and statistical physics. In the lab, amorphous materials are produced from a melt, following non-equilibrium quenches into the solid state. Amorphous materials are also produced in nature by self-assembly or by driven, active processes in biology, to impair functions such as structural color or mechanical stability.

Fundamental questions arise in how to describe material properties that depend on the processing history and on prevalent plastic responses. Also, many amorphous materials of technological interest as new functional materials are meso-structured, which renders them prone to strongly nonlinear and heterogeneous response even under moderate driving forces.

Theoretical approaches to describe such phenomena are routed in different approaches: one can start from the rheology of an increasingly viscous/visco-elastic fluid, or from the statistical mechanics of a low-temperature system with frozen disorder. The former approach naturally puts emphasis on temporal, non-Markovian history effects, while the latter emphasizes the role of spatial heterogeneities and elasto-plastic interactions. It is at the liquid-solid transition where these approaches need to meet, but it is still open how a unified physical picture emerges from this.

The aim of this Minerva school is to present to young researchers the various approaches that are relevant for dealing with amorphous materials, and to stipulate exchange between the different theories. This reflects recent research, for example the elaboration of the nonlinear rheology of deformable particles, the discovery of elastic stress- and strain-correlations even in the liquid, the elucidation of phonon transport and vibrational excitations in disordered media, or the addition of thermal effects to the deformation of amorphous solids.

Organising committee

Thomas Franosch, Universität Innsbruck, Austria

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Conference Coordinator

Inbal Azoulay, Weizmann Institute of Science, Israel

Abstracts of talks

Eran Sharon

The Racah Institute of Physics, The Hebrew University

The multi-scale nature of leaf growth - fluctuations, timescales and adaptation

A growing leaf is a fascinating system. It increases its area by orders of magnitudes while its elements – the cells- are not controlled by a central control system. Under these conditions it is highly nontrivial that leaves succeed in growing "properly" to the desired shape (in most cases flat). In order to achieve this, growth must be regulated locally, i.e., by some effective rheology.
We try to expose the characteristics of the growth field dynamics by measuring the evolving leaf surface with high spatio-temporal resolution. We find that the field is not smooth. It consists of sharp variation in growth rate and directionality, which include extensive shrinkage events as part of normal growth. We identify dominant time and length scales as well as qualitative differences between growth during day and night. We monitor giant variations in the growth rate due to environmental changes, such as transitions in illumination. These variations most likely result from stomatal activity, which involves overshooting and non-uniform spatial distribution. We, thus, suggest that stomatal activity is a central element in growth regulation.
In another set of experiments, we measure the effect of mechanical stress on leaf deformation and growth. The measured effective rheology is viscoelastic with time varying parameters. We provide evidences for the effect of stress on growth at different time scales. The effects include passive viscoelastic deformation at short times, growth correlated with stress during intermediated times and indications for tissue remodeling in response to extended application of mechanical stress.

Jeppe Dyre

Roskilde University, Denmark

The Tool-Narayanaswamy (TN) formalism for physical aging

This presentation provides an overview of the age-old TN material-time formalism. We present experimental as well as numerical data conforming to the simplest so-called "single-parameter" aging version of TN. We next discuss why the formalism works well for the description of aging involving moderate temperature variations and propose a "distance-as-time" interpretation of the material time.

Massimo Pica Ciamarra

Nanyang Technological Univerisy, Singapore

Excitations and relaxation in structural glasses

I will discuss how excitations influence the mechanical response of amorphous solids and the relaxation dynamics of structural glasses.
I will first illustrate numerical results suggesting that excitations defined in the linear or weakly-nonlinear response regime do not control the relaxation dynamics. I support this claim 1) by critically reviewing previous results; 2) by showing it is possible to influence the vibrational spectrum of (the inherent structures of) a glass without influencing its relaxation dynamics by minutely changing the interparticle interaction potential.
I will then turn my attention to non-linear excitations, defined as transitions between minima in the energy landscape. I will present results from a novel algorithm to identify these transitions and their activation energy. The increase in these barriers' activation energy upon cooling accurately allows for predicting the growth in relaxation time without any fitting parameter. This result suggests that local relaxation events, rather than collective ones, are responsible for glassy phenomenology

Edan Lener

University of Amsterdam, Netherlands

Strain-stiffening in athermal biopolymer networks

Athermal biopolymer networks are disordered fibrous biomaterials abundant in living cells and tissues that feature strong rigidity scale separation between the bending and stretching response of the constituent fibers. Such networks – that are generically underconstrained in terms of their degree of connectivity – undergo a dramatic macroscopic stiffening transition when subjected to sufficiently large external strains. In my talk I will present a complete scaling theory of the critical strain-stiffened state in terms of the small ratio between fiber bending and stretching/compression rigidities. I will show that the small bending forces may be viewed as an isotropic singular perturbation applied to the stiff anisotropic backbone corresponding to fibers' stretching/compression. The critical state features quartic anharmonicity, from which a set of nonlinear scaling relations for key observables are derived. These results, which are validated by numerical simulations, are then used to derive scaling predictions for the macroscopic elastic modulus beyond the critical state, revealing a previously unidentified characteristic strain scale. I will end by discussing a few open problems and the challenges they pose.

Michael Moshe

The Racah Institute of Physics, The Hebrew University, Israel

Screening by geometric charges in amorphous solids and metamaterials

Holes in elastic metamaterials, defects in 2D crystals embedded on planar or curved surfaces, and quasi- localized plastic deformations in amorphous matter are typical realizations of stress-relaxation mechanisms in different solids. Correspondingly, understanding the emergent hole patterns, defects structure, and mechanical response in these systems remains a formidable task. In a series of works we developed a generic screening theory of solids, in which local stress relaxations are modeled as induced elastic charges, similar to emergent dipoles in dielectric media. The theory is derived by incorporating into elasticity-theory new screening fields and constructing a Lagrangian that is consistent with the underlying system symmetries. Contrary to its electrostatic analog, the screening theory in solids is richer even in the linear case, with multiple screening regimes that lead to qualitatively new mechanical response. Here we provide a geometric derivation that identify the screening field as one that modifies the effective reference state.
Although the generic form of the screening theory allows us to test it in different physical systems, here we focus on amorphous solids. For example, we rigorously prove that mechanical strains in amorphous solids are screened via quadrupolar plastic events. Under certain conditions, e.g. large pressure, quadrupoles density is low, and the screening effect is reminiscent of dielectrics with elastic moduli being renormalized. At lower pressures quadrupole density is high, leading to qualitatively new mechanical response with emergent screening dipoles. We show that high-density screening results in displacement field that strictly deviate from elasticity theory thus interpreted as anomalous elasticity. We show that theoretical analysis, experimental measurements and numeric simulations of glasses and granular amorphous assemblies are in agreement with each other and provide a strong support for the theory. We conclude by discussing the relevance of our theory to other systems, such as wrinkles in thin sheets and elastic metamaterials.

Matthias Fuchs

Universität Konstanz, Germany

Driven colloidal glasses: Mode coupling theory on structural rearrangements in external fields

At the glass transition, particle rearrangements and transport processes become highly cooperative. External fields have strong effects, as the time scales of external drive and intrinsic structural rearrangements can easily be made to match. I review recent insights into the microscopic transport mechanisms in glass-forming systems obtained by nonlinear mechanical spectroscopy and by probe particle studies, forcing probe particles to move in amorphous environments. Generalizations of the mode coupling theory developed for quiescent liquids capture how the local arrested structures are affected by the external fields and provide a framework for the nonlinear response rationalizing many phenomena.

Gilles Tarjus

Université Pierre-et-Marie-Curie, France

The yielding transition of amorphous solids: From brittle to ductile through a critical point

To be announced soon.

Jay Fineberg, and Shahar Gvirtzman

The Racah Institute of Physics,The Hebrew University, Israel

The Fundamental Physics of the Onset of Frictional Motion: How does friction start?

Recent experiments have demonstrated that rapid rupture fronts, akin to earthquakes, mediate the transition to frictional motion. Moreover, once these dynamic rupture fronts ("laboratory earthquakes") are created, their singular form, dynamics and arrest are well-described by fracture mechanics. Ruptures, however, need to be created within initially rough frictional interfaces, before they are able to propagate. This is the reason that "static friction coefficients" are not well-defined; frictional ruptures can nucleate for a wide range of applied forces. A critical open question is, therefore, how the nucleation of rupture fronts actually takes place. We experimentally demonstrate that rupture front nucleation is prefaced by slow nucleation fronts. These nucleation fronts, which are self-similar, are not described by our current understanding of fracture mechanics. The nucleation fronts emerge from initially rough frictional interfaces at well-defined stress thresholds, evolve at characteristic velocity and time scales governed by stress levels, and propagate within a frictional interface to form the initial rupture from which fracture mechanics take over. These results are of fundamental importance to questions ranging from earthquake nucleation and prediction to processes governing material failure.

Annette Zippelius

Universität Göttingen, Germany

Emergence of Long-Ranged Stress Correlations at the Liquid to Glass Transition

A theory for the nonlocal shear stress correlations in supercooled liquids and colloidal suspensions is derived from first principles. It captures the crossover from viscous to elastic dynamics at an idealized liquid to glass transition and explains the emergence of long-ranged stress correlations in glass, as expected from classical continuum elasticity. Whereas Eshelby's elasticity pattern is recovered independently of the dynamics, the Goldstone modes differ drastically: Newtonian dynamics leads to propagating transverse sound, while the Goldstone modes of a colloidal glass are diffusive. Precursors of the long-ranged anisotropic stress correlations in the fluid can be observed in both cases. Their spatial extent can be characterized by a correlation length ξ, which grows like the shear viscosity η for a Newtonian fluid and like $\xi \propto \sqrt{\eta}$ in a colloidal fluid. These results are derived within a hydrodynamic theory, generalising Maxwell's model to finite wavenumbers, after the dynamics has been decomposed into potentially slow modes, associated with conservation laws and/or the order parameter, and fast microscopic degrees of freedom.

Yair Shokef

Tel Aviv University, Israel

Emergent Disorder and Mechanical Memory in Periodic Metamaterials

Ordered mechanical systems typically have one or only a few stable rest configurations, and hence are not considered useful for encoding memory. Multistable and history-dependent responses usually emerge from quenched disorder, for example in amorphous solids or crumpled sheets. In contrast, due to geometric frustration, periodic magnetic systems can espouse an extensive manifold of quasi-degenerate configurations. Inspired by the topological structure of frustrated artificial spin ices, we introduce an approach to design ordered, periodic mechanical metamaterials that exhibit an extensive set of spatially disordered states. Our mechanical systems encompass continuous degrees of freedom, and are hence richer than their magnetic counterparts. We show how such systems exhibit history-dependent and non-Abelain responses, as their state may depend on the order in which external manipulations were applied. Thus, multistability and potential to store complex memory emerge from geometric frustration in ordered mechanical lattices that create their own disorder.

Eran Bouchbinder

Weizmann Institute of Science, Israel

Driven frictional systems: Spatiotemporal rupture, unconventional singularities and scale separation

Macroscopic frictional systems are formed when two deformable bodies, e.g. two tectonic plates in the Earth's crust, undergo contact interaction along an interface that separates them. When driven externally, such systems exhibit rich spatiotemporal dynamics that emerge from the interplay between interfacial physics, involving strong dissipative and nonlinear frictional processes, and bulk physics, involving long-range elastodynamic interactions mediated by the deformable bodies. Macroscopic frictional interfaces are typically composed of an evolving ensemble of contact asperities whose collective dynamics give rise to glass-like behavior: frictional aging and rejuvenation, and rate-dependent rheology. In this overview talk, we discuss the recent progress we made in understanding the qualitative effect of the rate dependence of friction and its aging properties, when coupled to bulk elastodynamics, on the spatiotemporal failure dynamics of frictional systems. In particular, we discuss the origin of residual stresses, the emergence of unconventional rupture singularities (different from those associated with bulk materials failure), lengthscale separation related to rupture-induced dissipation and the style of rupture (crack-like vs. pulse-like).

Frank Scheffold

University of Fribourg, Switzerland

Glass formation and jamming in soft particle suspensions: from emulsions to microgels

We study the microscopic dynamics and rheology of glass-forming suspensions composed of micron-sized soft particles. We monitor the transition to the glass phase followed by the jamming transition by precisely controlling the sample composition, with an accuracy of better than 0.5% (absolute) or 0.3% (relative) [1]. In a separate experiment, we drag individual colloidal polystyrene probe particles seeded in a refractive index and buoyancy- matched emulsion to study the driven or 'active' motion in fluid and glass states [2]. Our experiments reveal intermittent dynamics around a de-pinning transition at a threshold force. To probe the motion in jammed emulsions at higher densities, we use diffusing wave spectroscopy (DWS) [3]. We develop an improved DWS analysis scheme, taking into account collective scattering contributions, which allows us to measure the bounded translational motion of crowded oil droplets accurately. The results we obtain for the elastic shear moduli, based on a generalized Stokes-Einstein relation (GSER), match very closely with mechanical measurements and model predictions as the droplets become more tightly jammed. We also study the influence of adding attractive forces leading to a reentrant phase transition from glass to liquid to gel [4]. Poly(N- isopropyl acrylamide) microgels are a different class of compressible soft colloidal particles we study. Here, we present results from in-situ two-color superresolution microscopy of dye-labeled submicron-sized pNiPAM microgels with a lateral optical resolution of 30nm. We map out the different contributions that allow the dense packing of the soft microgels due to deformation, interpenetration, and compression [5]. Based on the detailed understanding of the local structure and morphology, we can model the macroscopic rheological properties of dense suspensions over a broad range of densities. Our results suggest that friction between the microgels is reduced due to lubrification by the polymer brush-like corona before the onset of interpenetration. Finally, I will comment on the applications of soft particle glasses for materials science, structural color, and bandgap materials [6]. The properties of such materials benefit from short-range structural correlations and emerging hyperuniformity near jamming [7].

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Yoav Lahini

Tel Aviv University, Israel

Slow relaxations, aging, and memory formation in disordered mechanical systems

To be announced soon.

Elisabeth Agoritsas

EPFL, Switzerland

Dynamical Mean-Field Theory of many-body particle systems

Disorder is ubiquitous in physical systems, and can radically alter their physical properties compared to their 'pure' counterparts. For instance, amorphous materials such as emulsions, foams, metallic glasses or biological tissues are all structurally disordered, and this has key implications for their rheological, mechanical or transport properties. Nevertheless, theoretical descriptions of such 'driven' amorphous materials remain challenging, despite decades of extensive analytical and computational studies. The difficulties pertain to the interplay of competing sources of stochasticity, and to the resulting out-of-equilibrium nature of these systems.
A minimal model for amorphous materials, which allows to focus generically on the key role of their structural (positional) disorder, is provided by dense many-body systems of pairwise interacting particles. The limit of infinite spatial dimension then plays a very special role: it uniquely provides exact analytical benchmarks (otherwise scarce) for features of amorphous materials. Those include for instance the critical scalings in the vicinity of the jamming transition, the stress-strain curve of glasses under quasistatic shear, or their equilibrium phase diagramme depending on their temperature and/or packing fraction. Yet, the limit of infinite spatial dimension remains quite abstract. What is the relevance of these benchmarks for our two- or three-dimensional physical world?
In the last couple of years we derived an exact set of equations for a 'dynamical mean-field theory' (DMFT) of these models, paving the way to a dynamical understanding not only of previous (static) results, but also of any out-of-equilibrium driving protocol. Here I will introduce this DMFT formalism for particle systems, and briefly review what has been and remains to be done. I will in particular rely on a direct connection that we were able to establish, between sheared passive systems and active matter mechanical response, to provide some intuition on the validity of these infinite-dimensional predictions for low-dimensional systems. These results hint at a unifying framework for establishing rigorous analogies, at the mean-field level, between different families of driven disordered systems, such as sheared granular materials and active matter, or machine-learning algorithms.

Avraham Moriel

Weizmann Institute of Science, Israel

Extracting the Core Properties of Quasilocalized Glassy Excitations

Low-frequency nonphononic modes and plastic rearrangements in glasses feature a disorder-induced short-range core and known long-range decaying elastic fields. Extracting the unknown short-range core properties is of prime importance. We consider a class of contour integrals, performed over the known long-range fields, specifically designed for extracting the core properties. We first show that, in typical computer glasses, the long-range fields of quasilocalized vibrational modes experience boundary effects related to the simulation box shape and the widely employed periodic boundary conditions. Image interactions induced by the periodic boundary conditions cause the fields' rotation and orientation-dependent suppression of their long-range decay. We then develop a continuum theory accounting for these effects and verify it by computer simulations in both 2D and 3D. The theory accounts for the finite-size boundary effects and at the same time allows the extraction of the short-range core properties, such as their typical strain ratios and orientation. Our results offer a useful tool for extracting the intrinsic core properties of nonphononic modes and plastic rearrangements in computer glasses.

David Richard

University Grenoble Alpes, France

The yielding transition of amorphous solids: From brittle to ductile through a critical point

The transition between necking-mediated tensile failure of glasses, at elevated temperatures and small strain-rates, and shear-banding-mediated tensile failure, at low temperatures and high strain-rates, is investigated using experiments on metallic glasses and atomistic simulations. We show – both experimentally and simulationally – that this transition occurs through a sequence of macroscopic failure patterns, including necking interrupted by cup-and-cone-like patterns and patterns where cup-and-cone structures and partial shear-banding coexist. Analysis of the spatiotemporal dynamics preceding failure, using large scale molecular dynamics simulations corroborated by experimental fractography, reveals how the collective evolution and mutual interactions of shear-driven localized plastic transformations and dilation-driven void/cavity formation give rise to various macroscopic failure modes.

Florian Vogel

University of Konstanz, Germany

Vibrational phenomena in glasses at low temperatures captured by field theory of disordered harmonic oscillators

We investigate the vibrational properties of topologically disordered materials by analytically studying coupled harmonic oscillators in the thermodynamic limit at T=0. Exploiting field theory, we build up a self-consistent field theory by analysing the Hessian utilizing Euclidean Random matrix theory. In accordance with earlier findings [Grigera et al. 2011], we take non-planar diagrams into account to correctly address multiple local scattering events. By doing so, we end up with a first principles theory that can predict the main anomalies of athermal disordered materials, i.e the Boson peak, sound softening and a transition from Rayleigh damping to a weaker dependence of the sound attenuation around the Ioffe-Regel limit. Additionally, we argue that Rayleigh-damping implies a localisation of the eigenvectors of the random matrices. This is explained by the hybridisation of the phonons with quasi-localised modes (QLMs), which we explicitly detect as an excess in the density of states in the hydrodynamic limit. Thus, we rationalise the vibrational properties of disordered materials on a microscopic scale.

Dor Shohat

Tel Aviv University, Israel

Slow relaxations in disordered mechanical systems - aging on the verge of instability

Slow relaxations are a hallmark of disordered systems trapped in far-from-equilibrium conditions. After a perturbation, many of these systems exhibit logarithmically slow relaxations of one or more of their macroscopic observables. These relaxations can span many time scales, from a fraction of a second to days and even years. However, the microscopic processes underlying this behavior and the reason for its ubiquity across many different systems remain unclear.
Through experiments in crumpled sheets and simulations of a simplified mechanical model, we reveal a general mechanism underlying slow relaxation phenomena. We show that under load, these systems self-organize to a metastable state which is poised on the verge of a local instability, where they can remain for long, but finite times. The system's relaxation advances via a series of instabilities, each resulting in an avalanche, occurring on short timescales compared to the typical waiting times between instabilities. Crucially, we find that these waiting times increase as the system relaxes, due to the release of internal stress that leads to a slow increase in the effective energy barriers. This, we show, naturally leads to an overall logarithmic relaxation.

Noemie Livne

The Racah Institute of Physics, The Hebrew University, Israel

To be announced soon

To be announced soon.

Chaviva Sirote
Tel Aviv University, Israel

To be announced soon

To be announced soon.

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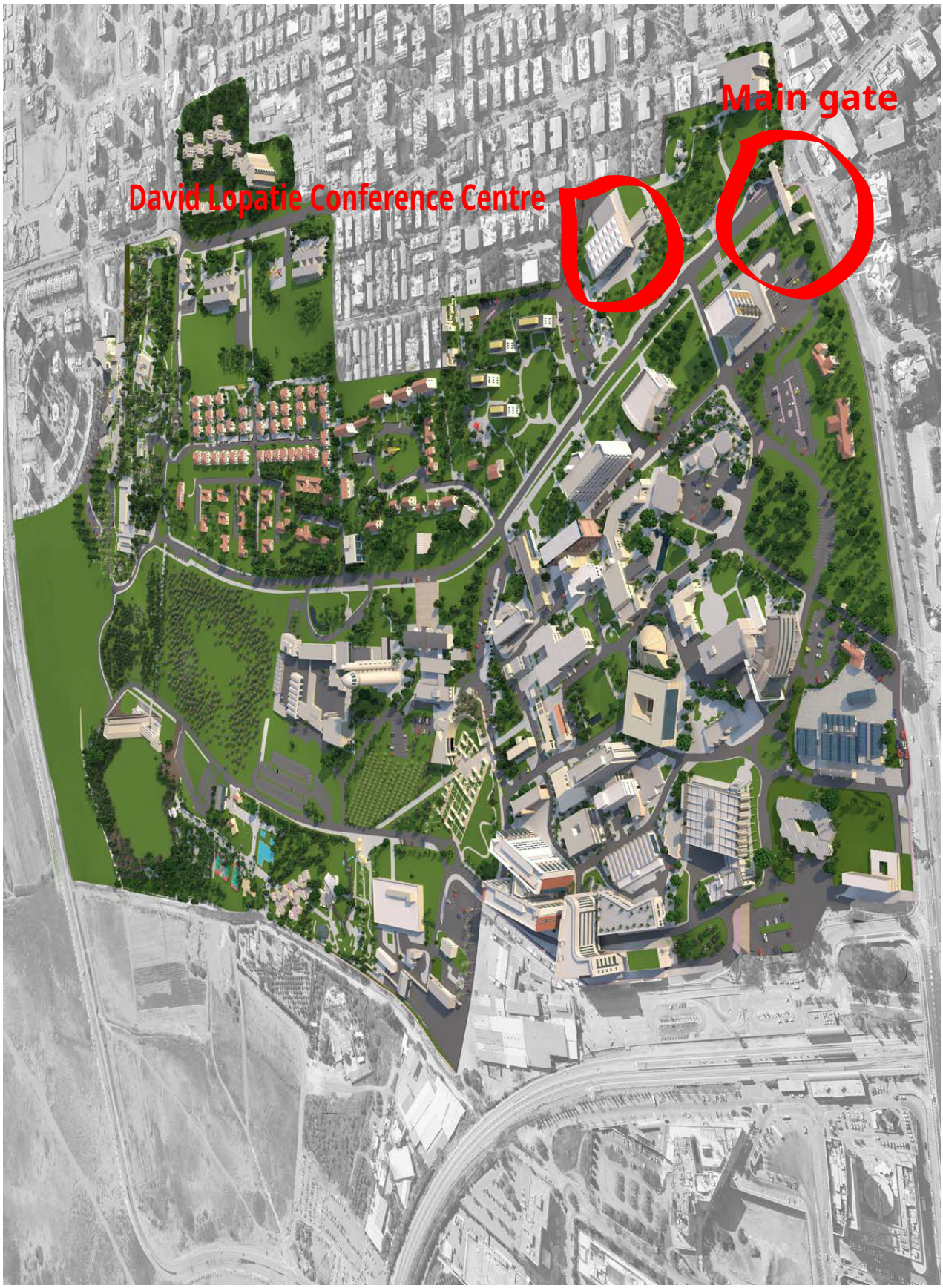
All events will take place at the David Lopatie Conference Centre (see map in next page for the navigation from the main gate)



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