List of talks and abstracts:

Workshop on high-dimensional Stochastics, WPI institute 7-9 September, 2020.

Plenary talks

Jochen Blath (Technical University Berlin).

Probabilistic structures emerging from dormancy

Abstract*: ….*

Christa Cuchiero (University of Vienna)

Universal properties of affine and polynomial processes

Abstract: We elaborate on the mathematical universality of affine and polynomial processes. In several recent works we could show that many models which are at first sight not recognized as affine or polynomial can nevertheless be embedded in this framework. For instance, all well-known measure-valued diffusions such as the Fleming–Viot process, the Super–Brownian motion, and the Dawson-Watanabe superprocess are affine or polynomial processes. In mathematical finance essentially all examples of (rough) stochastic volatility models can be viewed as (infinite dimensional) affine or polynomial processes. This suggests an inherent universality of these model classes. We try to make this mathematically precise by showing that generic classes of diffusion models with possibly path-dependent characteristics are projections of infinite dimensional affine processes (which in this setup coincide with polynomial processes). A key ingredient to establish this result is the so-called signature process, well known from rough paths theory.The talk is based on joint works with Sara Svaluto-Ferro and Josef Teichmann.

Sonja Cox (University of Amsterdam)

Simulation of generalized Whittle-Matern fields

Abstract: Whittle-Matern fields are a type of Gaussian random fields on $\mathbb{R}^d$. Their covariance operator is of the form $(\kappa - \Delta)^{-\beta}$, where $\kappa \in [0,\infty)$, $\beta \in (\frac{d}{4}, \infty)$, and Δ is the Laplacian. Whittle-Matern fields are popular models in spatial statistics and uncertainty quantification. In recent years, much research has been regarding efficient simulations of such fields. I will provide an overview of these results and explain my own contribution regarding the simulation of generalized Whittle-Matern fields. Joint work with Kristin Kirchner.

Victor Panaretos (EPFL Lausanne)

Testing for the rank of a covariance operator

Abstract: How can we discern whether the covariance operator of a random process is of reduced rank, and if so, what its precise rank is? And how can we do so at a given level of confidence? This question is central to a great deal of statistical methods for random processes, which require low-dimensional representations whether by PCA or other methods. The difficulty is that the determination is to be made on the basis of i.i.d. replications of the process observed discretely and with measurement error contamination. This adds a ridge to the empirical covariance, obfuscating the underlying dimension. We consider a matrix-completion inspired test statistic that circumvents this issue by measuring the best possible least square fit of the empirical covariance's off-diagonal elements, optimised over covariances of given finite rank. For a fixed grid of sufficiently large size, we determine the statistic's asymptotic null distribution as the number of replications grows. We then use it to construct a bootstrap implementation of a stepwise testing procedure controlling the family-wise error rate corresponding to the collection of hypotheses formalising the question at hand. Under minimal regularity assumptions we prove that the procedure is consistent and that its bootstrap implementation is valid. The procedure circumvents smoothing and associated smoothing parameters, is indifferent to measurement error heteroskedasticity, and does not assume a low-noise regime. Based on joint with with Anirvan Chakraborty (Indian Institute of Science Education and Research, Kolkata).

Markus Riedle (King's College, London)

Cylindrical Lévy processes and Lévy space-time white noises

Abstract: It is well known that the cylindrical Brownian motion and the Gaussian space-time white noise correspond to each other. In this talk we consider the analogue relation between cylindrical Lévy processes and Lévy space-time white noises. In contrast to the Gaussian case, it turns out that this correspondence only holds for specific kinds of cylindrical Lévy processes. We exploit the established relation by embedding cylindrical Lévy processes in certain Besov spaces, which may be seen as a first result explaining the regular (or irregular) behaviour of the jumps of a cylindrical Lévy process.

Contributed talks

Valentin Courgeau (Imperial College London)

High-frequency Estimation of the Lévy-driven Graph Ornstein-Uhlenbeck process

Abstract: We consider a particular Ornstein-Uhlenbeck process for graphs, the Graph Ornstein-Uhlenbeck (GrOU) process, observed on a non-uniform discrete time grid and introduce discretised maximum likelihood estimators with parameters specific to the whole graph or specific to each component, or node. Under a high-frequency sampling scheme, we study the asymptotic behaviour of those estimators as the mesh size of the observation grid goes to zero. We prove two stable central limit theorems to the same distribution as in the continuously observed case under both finite and infinite jump activity for the Lévy driving noise. When a graph structure is not explicitly available, the stable convergence allows to consider purpose-specific sparse inference procedures on the edges themselves in parallel to the GrOU inference and preserve its asymptotic properties. We apply the new estimators to wind capacity factor measurements across fifty locations in Northern Spain and Portugal. We compare those estimators to the standard least squares estimator through a simulation study extending known univariate results across graph configurations, noise types and amplitudes.

Tobias Fissler (Vienna University of Economics and Business WU)

Forecast Evaluation of Quantiles, Prediction Intervals and other Set-Valued Functionals

Abstract: We introduce a theoretical framework of elicitability and identifiability of set-valued functionals, such as quantiles, prediction intervals, and systemic risk measures. A functional is elicitable if it is the unique minimiser of an expected scoring function, and identifiable if it is the unique zero of an expected identification function; both notions are essential for forecast ranking and validation, and M- and Z-estimation. Our framework distinguishes between exhaustive forecasts, being set-valued and aiming at correctly specifying the entire functional, and selective forecasts, content with solely specifying a single point in the correct functional. We establish a mutual exclusivity result: A set-valued functional can be either selectively elicitable or exhaustively elicitable or not elicitable at all. Notably, since quantiles are well known to be selectively elicitable, they fail to be exhaustively elicitable. We further show that the class of prediction intervals and Vorob'ev quantiles turn out to be exhaustively elicitable and selectively identifiable. We give possibility and impossibility results for the shortest prediction interval and prediction intervals specified by an endpoint or a midpoint. The talk is based on the preprint https://arxiv.org/abs/1910.07912, which is joint work with Rafael Frongillo, Jana Hlavinova and Birgit Rudloff.

Matteo Gardini (University of Genoa)

Correlating Levy processes with Self-Decomposability: Applications to Energy Markets

Abstract: In this study we investigate the possibility of constructing multi-dimensional processes that are at least marginally L´evy, using multivariate subordination. To this end, several approaches are available in the literature, for instance Barndorff-Nielsen et al. [2] or Luciano and Schoutens [10] use a common subordinator. In particular, in a series of papers Semeraro [13], Luciano and Semeraro [11], Ballotta and Bonfiglioli [1], Buchmann et al. [3] and Buchmann et al. [4] have proposed models based on subordination to introduce dependence between L´evy process. The common idea of these papers is to define multi- variate processes that are the sum of an independent process and a common process. For example Ballotta and Bonfiglioli [1] define a multivariate process in the following way:

$$\mathbf{Y}(t) = (Y_1(t), \ldots, Y_n(t))^\top = (X_1(t) + a_a Z(t), \ldots, X_n(t) + a_n Z(t))^\top$$

where $Z(t), X_j(t), j = 1,\ldots, n$ are independent Levy processes. In a financial market, one can see the common process $Z(t)$ as a systemic risk, whereas the independent processes $X_j(t)$ can be considered as an idiosyncratic component. The model has a simple economical interpretation and it is mathematically tractable.

The technique proposed by Semeraro [13] and Luciano and Semeraro [11] is very similar but it is applied on subordinators. Semeraro [13] defines the process $Y(t)$ as:

$$\mathbf{Y}(t) = (Y_1(t), \ldots, Y_n(t))^\top = (W_1(G_1(t)), \ldots, W_n(G_n(t))^\top$$

where $W_j(t), j = 1,\ldots,n$ are independent BM and $G_j(t), j = 1,\ldots,n$ are subordinators.
Each of these subordinators $G_j(t)$ is built as:

$$G_j(t) = X_j(t) + \alpha_j Z(t), j = 1,\ldots,n$$

where $Z(t), G_j(t), j = 1,\ldots,n$ are independent subordinators and $\alpha_j \in \mathbb{R}^+, j = 1,\ldots,n$.
Since the correlation obtained with this model might not be as high as the one observed in the market (see Wallmeier and Diethelm [14]), Luciano and Semeraro [11] use the same technique proposed by Semeraro [13] but applied to correlated BM 's.

The purpose of this study is to extend these models using self-decomposable (sd) subordinators: the idea is to replace the common process $Z(t)$ by depended processes $H_1(t), \ldots, H_n(t)$. These processes are built using the notion of sd that provides an easy way to correlate random variables (rv). This construction allows us to introduce a new market dynamic similar to that observed in Cufaro Petroni and Sabino [6]: the processes $(H_1(t), \ldots, H_n(t))$ can be interpreted as news in the market occurring with random delays therefore, this can help us modeling co-movements in the markets.

Indeed, once a market receives a news (or shock) after a certain random delay we observe a propagation onto another market. We refer to this new type of processes as synaptic processes as proposed by Cufaro Petroni and Sabino [7].

We show that our approach preserves mathematical tractability, indeed, we can derive the characteristic functions, the linear correlation coefficient and design algorithms to simulate these processes in the case of Gamma and Inverse Gaussian subordinators using algorithms proposed by Cufaro Petroni and Sabino [8] and Zhang and Zhang [15] respectively. It is also worthwhile observing that our model goes beyond the mathematical generalization of the original ones provided by Buchmann et al. [3] and Buchmann et al. [4]: they analyze the case where the subordinator is sd. As it will be clear from the sequel, the a-reminder part of the subordinator $H_j(t), j > 1$ process is infinitely divisible but not sd.

We then apply our market models to the pricing of spread options that are common derivative contracts in energy markets. Since spread options are often not liquid enough, all our models are calibrated using a two-step methodology: firstly, one calibrates the marginal parameters on quoted vanilla products and then, one fits the correlation structure using historical quotations. Moreover, for these models some standard pricing techniques based on the Fourier transform for multivariate setting (see for instance Hurd and Zhou [9], Caldana and Fusai [5] and Pellegrino [12]), or Monte Carlo (MC) methods are available. This is joint work with Piergiacomo Sabino and Emmanuela Sasso,

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Michele Giordano (University of Oslo)

Lift of Volterra processes: optimal control and HJB equations

Abstract: The goal of this paper is to maximize a performance functional of the form

(1) $$J(t,u,x) = \mathbb{E}\left[\int_t^T F(s, X_s^u, u_s)ds + G(X_T^u)\right]$$

over an admissible control set, where the dynamics of the forward process are given by

(2) $$X_t^u = x + \int_0^t K(t-s)(\beta'(s, X_s^u, u_s)ds + \sigma(s, X_s^u)dW_s), \qquad t \in [0,T]$$

for $x \in \mathbb{R}$ and β' and σ some real valued functions. Being the forward equation of Volterra type, the system is not Markovian, which means that one cannot apply directly the dynamic programming principle.

In order to be able to recover a dynamic programming principle, we start by introducing a lift for the process (2), similar to the one introduced in [1-2], that allows us to recover some Markov properties by rewriting the forward dynamics in a infinite dimensional (Banach) setting.

Once we reformulated the whole optimization problem (1)-(2) in the Banach setting, we proceed to deduce a dynamic programming principle for the lifted problem. With an approach similar to the one presented in [3-4], we obtain the Hamilton-Jacobi-Bellman equations corresponding to the lifted optimization problem, and we are able to find the optimal control in the infinite dimensional setting.

Lastly we show that one can go back to the initial real valued problem and characterize the optimal control u of the optimization problem (1) in terms of the solution of the lifted optimization problem.

Examples and applications will be presented. This is joint work with Giulia Di Nunno.

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Silvia Lavagnini (University of Oslo)

Accuracy of Deep Learning in Calibrating HJM Forward Curves

Abstract: We price European-style options written on forward contracts in a commodity market. We follow the Heath-Jarrow-Morton (HJM) approach and model the forward curve by a stochastic partial differential equation with state-dependent volatility, and having values in the Filipović space [5]. In our setting, the Hilbert valued Wiener process driving the noise of the forward curve takes values in $L^2(\mathcal{O})$, $\mathcal{O}$ being some Borel subset of $\mathbb{R}$ (possibly $\mathbb{R}$ itself). This requires that the volatility operator must smoothen elements in $L^2(\mathcal{O})$ into elements of the Filipović space. We achieve this by constructing the volatility as an integral operator with respect to some kernel function, and derive the conditions needed on the kernel function such that the volatility operator is well defined. We then focus on the pricing of forward contracts with delivery period, also called swaps. Typical examples are forward contracts in the electricity market, such as the ones traded at Nord Pool AS and the European Energy Exchange (EEX). For a deterministic volatility structure, we derive analytic pricing formulas based on a representation theorem for swaps presented in [2]. For a state-dependent stochastic volatility operator one needs instead to resort to simulation schemes for stochastic partial differential equations.

Our fully parametrized model allows for pricing and calibration based on deep neural networks. Therefore we adopt the approach presented in [1] to our setting, and approximate the pricing functional with a neural network in a (possibly) costly off-line step. After training, the neural network is used to recover the model parameters in an optimization routine. The calibrated parameters can then be used together with the trained neural network for pricing options that are not traded on the exchange. Resorting to neural networks for both, the calibration and the pricing step, offers critical computational advantages for those models requiring more expensive techniques, such as Monte Carlo techniques. In fact, in this neural network approach, the computationally expensive simulation is only required to generate the training set in the learning process of the network, and is not needed for intraday calibration and pricing.

We perform a comprehensive case study of our framework and analyse the accuracy of neural networks for pricing and calibration in the infinite dimensional HJM setting. To avoid a training set based on large scale Monte Carlo simulation, which introduces additional sources of error, we restrict our focus on a deterministic but time dependent volatility operator. To our knowledge, this is indeed the first application of deep neural networks in an infinite dimensional HJM setup for the purpose of model calibration. We consider two different approaches both presented in [1], the pointwise and the grid-based learning approach, and we compare dense and convolutional neural

network architectures. We then extend the framework to allow for calibration with a wide bid and ask spread, where using a mid price is not feasible. The problem of wide bid-ask spreads is particularly pronounced in energy markets, since only the front end swaps are traded liquidly.

In the approximation step, we observe a high degree of accuracy, with an average relative error for the test set in the range 0.3%-3%. The picture is different when it comes to calibration. Here the trained neural network might fail to recover the true parameters, and we do indeed observe average relative errors reaching almost 50% in some cases. On the other hand, the prices estimated after calibration have an average accuracy around 5%. This failure in recovering the parameters is the result of two effects, one specific to the model and one to the network. In the specified model, several parameter vectors lead to similar prices for the training set, making it difficult to recover the true parameters. However, we also show that the trained neural network can be non-injective in the input parameters to a degree not justified by the original model. For instance, keeping all but the volatility scaling fixed, the call price should be an increasing function of volatility. This in fact is not always the case. Given that no-arbitrage conditions are not imposed on the neural network, this is actually not surprising, but contributes to the problem of calibration. It may cause the original meaning of the parameters to get lost in the approximation step, and shows that careful benchmarking is required when using the neural network approach for calibration, in particular for pricing more complicated options.

For the calibration in markets with large bid-ask spread, the simple loss function proposed here seems to work well. We test it with respect to different bid-ask spread sizes, and in fact, after calibration, almost all prices lie within the bid-ask range and only few are outside, but still very close to either the bid or the ask price. In particular, whenever the bid-ask spread becomes more narrow, one can simply increase the number of iterations for the optimization routine to obtain good results. The optimization is fast because it does not require any simulation. Moreover, the observed errors in recovering the parameters are not increasing dramatically as compared to the calibration based on a zero bid-ask spread. The full text is available at: https://arxiv.org/abs/2006.01911. This is joint work with Fred Espen Benth and Nils Detering.

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Stefan Rigger (University of Vienna)

Propagation of Minimality in the Supercooled Stefan Problem

Abstract: The one-dimensional one-phase Supercooled Stefan Problem is a PDE problem with free boundary which serves as a model for the freezing of supercooled liquids. Under certain conditions, this model will exhibit blow-up in finite time. Following the methodology of Delarue, Nadtochiy and Shkolnikov, we construct solutions to the Supercooled Stefan Problem through the Fokker-Planck equation associated to a stochastic process that solves a certain McKean-Vlasov equation. This technique allows us to define solutions globally even in the presence of blow-ups. Solutions to the associated McKean-Vlasov equation can be constructed via an approximating particle system, and we prove Propagation of Chaos. The particle system in question appears in the literature on systemic risk, establishing the connection of the aforementioned results to Mathematical Finance. Finally, we prove a conjecture of Delarue, Nadtochiy and Shkolnikov, relating the solution concepts of so-called minimal and physical solutions, showing that minimal solutions of the McKean-Vlasov equation are physical whenever the initial condition is integrable.

Piergiacomo Sabino (E.ON)

Fast Pricing of Energy Derivatives with Mean-reverting Jump-diffusion Processes

Abstract: Most energy and commodity markets exhibit mean-reversion and occasional distinctive price spikes, which results in demand for derivative products which protect the holder against high prices. To this end, in this paper we present exact and fast methodologies for the simulation of the spot price dynamics modeled as the exponential of the sum of an Ornstein-Uhlenbeck and an independent pure jump process, where the latter one is driven by a compound Poisson process with (bilateral) exponentially distributed jumps. These methodologies are finally applied to the pricing of Asian options, gas storages and swings under different combinations of jump-diffusion market models, and the apparent computational advantages of the proposed procedures are emphasized. Joint work with Nicola Cufaro Petroni.

Dennis Schroers (University of Oslo)

Copulas and Sklar's Theorem in infinite dimensions

Abstract: Copulas describe statistical dependence between the components of multivariate random variables in full generality by virtue of Sklar's theorem. Although they are used and defined for certain infinite dimensional objects (e.g. Gaussian processes in [WG10], Markov processes in [DNO92], [Ibr09] and [L10], or copulas in Hilbert spaces in [HR17]) there is no prevalent notion of a copula as an infinite dimensional law that unifies these concepts. To this end we define copulas as probability measures on product spaces $\mathbb{R}^I$ for some index set I and formulate Sklar's theorem in this general setting. An important application is the task of modeling the inherent dependence of random variables in function spaces. In Banach spaces (or more general topological vector spaces) already the notion of marginals becomes ambiguous: Take the example of the space $C[0,1]$. it is possible to emded this space into the product space $\mathbb{R}^{[0,1]}$ of real functions on $[0,1]$ via

(1) $f \mapsto (f(x))_{x\in[0,1]}$

At the same time, the existence of a Schauder basis in this space makes it possible to embded it into the space $\mathbb{R}^{\mathbb{N}}$ of real sequences via

(2) $f \mapsto (e_n(f))_{n\in\mathbb{N}}$

for the coefficient functionals $(e_n)_{n\in\mathbb{N}}$ of the Schauder basis. Both embeddings lead to reasonable notions of marginals of a measure μ on $C[0,1]$, either as the laws $(\mu(\delta_x^{-1}\cdot)_{x\in[0,1]}$ for the

evaluation functionals $\delta_x h = h(x)$, as well as $(\mu(e_n^{-1}\cdot)_{n\in\mathbb{N}}$. For this reason, copula on function spaces have to be considered for each of such a proper dual subset separately, depending on the respective modeling task.

In finite dimensions the second part of Sklar's Theorem enables us to construct probability measures by merging arbitrary marginals and dependence structures (in form of copulas). This simple construction cannot be transferred into the infinite dimensional setting of function spaces without any problems: Taking a set of marginals $(\mu(\delta_x^{-1}\cdot)_{x\in[0,1]}$ in terms of the function embedding (1) on $C[0,1]$, and a set of absolutely continuous marginal distributions $(F_t)_{t\in[0,1]}$, we need these marginals to be continuous in distribution, that is $t \mapsto F_t(x)$ has to be continuous for each $x \in \mathbb{R}$. This is clearly not the case for every choice of marginals and the constructed measure would rather be a cylindrical premeasure on $C[0,1]$.

We will therefore provide criteria to decide if the construction induced by the second part of Sklar's theorem yields certain properties like the regularity of paths and culminates in a real probability law in a function space. In addition, following [CARTD93] and [AJ14], we link our concept of copulas to Wasserstein distances. Namely, underlying copulas of probability laws in l^p -sequence spaces with finite pth moment effectively solve a marginal-restricted optimisation problems in the pth Wasserstein space. This is joint work with Fred Espen Benth and Giulia Di Nunno.

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Carlo Sgarra (Politecnico di Milano)

A Barndorff-Nielsen and Shephard Model with Leverage in Hilbert Space for Forward Power Market

Abstract: We propose an extension of the model proposed by Benth, Ruediger and Suss [3], based on stochastic processes of Ornstein-Uhlenbeck taking values in Hilbert spaces, including the leverage effect. We compute explicitly the characteristic function of the logreturn and the volatility processes. By introducing a measure change of Esscher type we provide a relation between the dynamics described with respect to the historical and to the risk-neutral measure. By following the approach outlined by Benth and Kruehner [1], [2], we discuss the application of the model proposed to describe power forward curves dynamics in a Heath-Jarrow-Morton

framework. We show how the Conditional Gaussianity of the BNS model offers a simple a direct approach to option pricing in an infinite-dimensional setting as well and discuss some examples. This is joint work with Fred Espen Benth.

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Yoav Zemel (Cambridge University)

Probabilistic approximations to optimal transport

Abstract: We propose a simple subsampling scheme for fast randomized approximate computation of optimal transport distances on finite spaces. This scheme operates on a random subset of the full data and can use any exact algorithm as a black-box back-end, including state-of-the-art solvers and entropically penalized versions. We give non-asymptotic deviation bounds for its accuracy in the case of discrete optimal transport problems, and show that in many important instances, including images (2D-histograms), the approximation error is independent of the size of the full problem. We present numerical experiments demonstrating very good approximation can be obtained while decreasing the computation time by several orders of magnitude. Further results on the transport plan itself will be briefly mentioned.