Maximum entropy models for financial systems

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Cover Page

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Concluding Remarks

In this thesis, we have reviewed various maximum-entropy models and their applications to different complex systems. We have demonstrated how flexible, and yet powerful, this approach is when applied to different systems. The foundations on which our maximum-entropy method is built come from deep within statistical physics. The models essentially describe canonical ensembles of different matrices representing time series, multiple time series, and various types of networks, which maximize Shannon's entropy given some constraints. As a result, for a given choice of constrains, the method characterizes each system with a unique probability distribution. Remarkably, dependent on the amount of partial information a model preserves, it can then be used in various ways, from statistical inference to empirical modelling and data filtration.

This takes us back to the main research question of the thesis, where we wanted to introduce a new class of statistical models which are as heterogeneous as real-world systems. We applied our models to complex financial systems covering different scales from the "microscopic" resolution of single stocks (time series) to the mesoscopic resolution of correlated communities of stocks, and finally to the macroscopic scale of entire economic networks. For each system, we identified the specific problems and challenges, which led us to a specific maximum-entropy approach in each setting.

In Chapter 1, we analysed financial time series and their corresponding binary projections. In this setting, the models enabled us to characterize and quantify the amount of information encoded in the binary signatures. We measured and compared the performance of the different models, indicating which property encodes more information, i.e. has the highest probability to replicate the original time series. When applied to cross-sections of financial time series, our method identified distinct regimes in the collective behaviour of groups of stocks, corresponding to different levels of coordination that only depend on the average return of the binary time series. Moreover, each regime is characterized by the most informative property. Finally, using the models we were able to mathematically characterize a universal relation between binary and non-binary properties for financial time series. These findings suggest that binary signatures of financial

time series carry significant information, and present a new coordination measure in financial markets. The results in this chapter provided both the theoretical formalism and the motivation for the studies in chapter 3.

In chapter 2, we focused on the International Trade Network. We exploited the power of the maximum-entropy model in reproducing the complex large-scale topology of the empirical system and combined it with a more popular approach of macroeconomics models which focuses on individual link weights instead. Indeed, macroeconomic models have mainly concentrated on the expected volume of trade between two countries, given certain macroeconomic properties, and have disregarded the topology in which the system is embedded. As a result, the model's outcome is inconsistent with the observed, complex, topology of the ITN. Here, we assigned an accurate macroeconomic interpretation to the Lagrange multipliers which control for the number and weight of the links of each node in the maximum-entropy ensemble. In turn, this led to a new set of topologically invariant network models, which reformulate otherwise ill-defined economic models in such a way that the expected network topology does not depend on the arbitrary choice of the units of link weights. Lastly, this formula is general and can be applied to any economic network for which an empirically well-established econometric model for the link weights exists.

In chapter 3, maximum-entropy models were used as a random benchmark for filtering empirical correlation matrices. We have generalized a community detection method using the maximum-entropy formalism, resulting in an improved null model for the detection of non-random properties in the correlation matrix. Next, we applied the method to financial markets trying to uncover the community structure encoded within the binary signatures of financial time series. The analysis shows that in financial markets both the binary and weighted representations shared similar spectral properties, and formed very similar structures. Thus, indicate that the binary description of financial time series encodes significant structural information. The results motivate the use of binary projections, which are much more robust to noise than the original full data, for identifying non-trivially correlated groups of stocks. Finally, we tested the method in a biological setting applying it to the biological clock of mice, a complex network of oscillating neurons, uncovering a functional core-periphery structure which has been validated independently. We have shown that alternative state-of-the-art methods fail in detecting such core-periphery structure, as they only identify a radial gradient of connectivity decreasing from the centre towards the periphery, with no sharp boundary in between. Our approach enhances the identification of models and structure in functional brain networks, facilitating a more refine network analysis on the level of single neurons.

To conclude, the findings in this thesis emphasize the strength of the maximum-entropy approach when applied to complex systems. This research motivates

further exploration of more sophisticated maximum-entropy models and the introduction of new tools to characterize heterogeneous and non-stationary systems. Such models have a great potential to make an impact in the fields of finance, economics, and neuroscience.