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Transfer learning from Hermitian to non-Hermitian quantum many-body physics

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Abstract

Identifying phase boundaries of interacting systems is one of the key steps to understanding quantum many-body models. The development of various numerical and analytical methods has allowed exploring the phase diagrams of many Hermitian interacting systems. However, numerical challenges and scarcity of analytical solutions hinder obtaining phase boundaries in non-Hermitian many-body models. Recent machine learning methods have emerged as a potential strategy to learn phase boundaries from various observables without having access to the full many-body wavefunction. Here, we show that a machine learning methodology trained solely on Hermitian correlation functions allows identifying phase boundaries of non-Hermitian interacting models. These results demonstrate that Hermitian machine learning algorithms can be redeployed to non-Hermitian models without requiring further training to reveal non-Hermitian phase diagrams. Our findings establish transfer learning as a versatile strategy to leverage Hermitian physics to machine learning non-Hermitian phenomena.

Supplementary material for this article is available online

Keywords: machine learning quantum matter, non-Hermitian physics, topological states

1. Introduction

The interplay between various degrees of freedom in many-body systems results in the emergence of novel phases of matter, including superconducting [1–6], Mott insulating [7–11], nematic [12–16] and topological [17–22] phases. Due to their inherent complexity, these systems are often studied computationally, using, e.g. quantum Monte Carlo methods [23–25] and tensor network approaches [26–28]. In recent years, machine learning methods [29, 30] have provided a complementary strategy to rationalize phases of matter, often in combination with conventional quantum many-body methods. The demonstrations of these roles played by machine learning methods in tackling many-body problems results in characterizing different phases of matter [31–40], deep learning of the quantum dynamics [41–44], obtaining many-body wave functions [45–49], and optimizing the performance of computational simulations [50].

Exploring correlated physics in open quantum systems attracts great interest mainly because of the systematic treatment of loss and gain in these systems, which quantitatively reproduces experimental observations [51–55]. In recent years, along with brute force studies of open quantum systems, understanding their effective descriptions based on non-Hermitian physics get momentum [56–61]. The studies of

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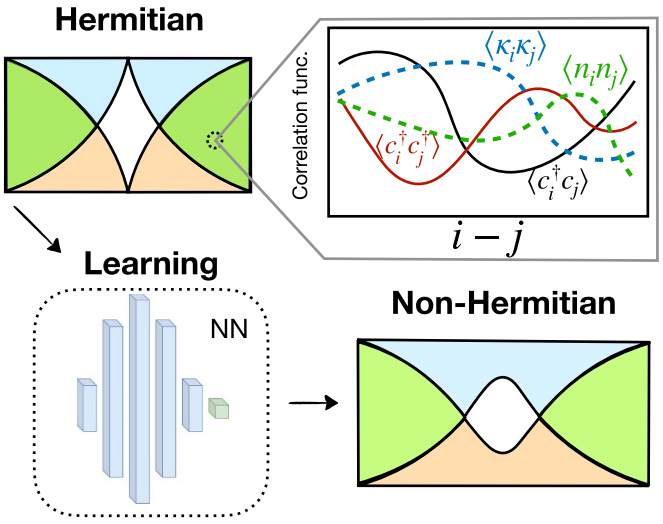

Figure 1. Non-Hermitian transfer learning: schematic illustration of the transfer learning methodology from Hermitian models to non-Hermitian physics. As an input, for each point of the phase diagram of the Hermitian model, short-range two-point (solid lines) and four-point (dashed lines) correlation functions are computed (equations (4) and (5)). The generated correlators for Hermitian systems are used to train a machine learning architecture, which in turn allows predicting the phase diagram from short-range correlators of the non-Hermitian model. The machine learning methodology allows extracting quasi-degeneracies and correlation entropies from the short-range correlators of the non-Hermitian model.

non-Hermitian models have initially focused on single-particle models [62–80], and its extension to the fully interacting realm has also gained attention recently [81–97]. Aside from these case studies, unraveling the physics of interacting non-Hermitian systems remains an open challenge due to the scarcity of exactly solvable models, and as conventional (Hermitian) many-body methods cannot be directly applied to the non-Hermitian limit. Specifically, obtaining the phase boundaries, understanding the stability of certain phases against non-Hermiticity, and characterizing exotic phases with no Hermitian counterparts remain in general open problems. Similar to the realm of Hermitian physics, machine learning methods, and specifically supervised [98–101], unsupervised [101, 102], and graph-informed methods [103] allowed to identify various phases of non-Hermitian non-interacting systems. In these methodologies, the inputs to train learning models are collected from non-Hermitian noninteracting systems and are used to characterize non-Hermitian phase diagrams. As computational methods for Hermitian interacting models are numerically less demanding and more stable than their non-Hermitian counterparts, learning phase diagrams of non-Hermitian many-body systems from Hermitian correlated models would open up a promising strategy to leverage many-body methods developed for interacting Hermitian models.

In this manuscript, we show that machine learning methods purely trained on Hermitian many-body data can predict interacting regimes in non-Hermitian interacting models. For concreteness purposes, we explore the different regimes of the non-Hermitian dimerized Kitaev-Hubbard chain using machine learning techniques schematically shown in figure 1. Here, we collect various correlation functions, orders of quasi-degeneracies, and correlation entropies at different parameter regimes of the Hermitian limit of our model. Using this input, we demonstrate that non-Hermitian regime crossovers can be identified using a machine-learning methodology trained on short-range Hermitian correlation functions. The outcomes of these supervised learning schemes are degrees of quasi-degeneracies and correlation entropies, which can characterize various regimes of the non-Hermitian model. Our findings reveal that employing correlation entropy as a classifier allows characterizing all regimes of the system. Our machine-learning approach reliably learns various regimes that share similarities with the Hermitian model. Our method also successfully delineates the regime crossovers even when the correlation effect in the non-Hermitian interacting model deforms the Hermitian phase diagram.

2. Non-Hermitian interacting model

We focus on an interacting non-Hermitian model whose phase boundaries can be solved exactly in the thermodynamic limit [93]. The non-Hermitian dimerized Kitaev–Hubbard Hamiltonian on a chain with length L is given by

$$\mathcal{H} = -\sum_{j=1}^{L-1}\left[t_j\left(c_j^\dagger c_{j+1} + c_{j+1}^\dagger c_j\right) + \Delta_j\left(c_j^\dagger c_{j+1}^\dagger + c_{j+1}c_j\right)\right] + \sum_{j=1}^{L-1}\left(U_j - \mathrm{i}\delta_j\right)\left(2n_j - 1\right)\left(2n_{j+1} - 1\right), \quad (1)$$

where $c_j^\dagger$ (c_j) is a creation (annihilation) operator for spinless fermion at site j associated with the fermion density $n_j = c_j^\dagger c_j$. Here t_j, Δ_j, and $U_j - i\delta_j$ denote, respectively, real-valued dimerized hopping amplitude, superconducting pairing amplitude, and complex-valued Hubbard interaction strength. Considering the site-independent parameter $\mathcal{O} \in \{t, \Delta, U, \delta\}$, $\mathcal{O}_j \in \{t_j, \Delta_j, U_j, \delta_j\}$ for $1 \leqslant j \leqslant L$ reads $\mathcal{O}_j = \mathcal{O}(1-\eta)$ if $j \bmod 2 = 0$ and $\mathcal{O}_j = \mathcal{O}(1+\eta)$ if $j \bmod 2 = 1$, where η is the real-valued dimerization parameter.

The Hamiltonian in equation (1) is exactly solvable when $\Delta = t$. At this parameter regime, the interacting model can be mapped to a quadratic fermionic model upon successive two Jordan-Wigner transformations and a spin rotation [93]. Through this procedure, one can show that the spectrum of the effective quadratic Hamiltonian undergoes gap closure upon setting $\frac{U}{t} = \pm\sqrt{\left|\frac{\delta^2}{t^2} - \frac{(1\pm\eta)^2}{(1\mp\eta)^2}\right|}$, and $\frac{U}{t} = \pm\frac{1\pm\eta}{1\mp\eta}$. These relations ensure the closure of the real-line gaps and the appearance of zero degeneracies in the imaginary part of the spectrum, respectively. Note that these two equations coincide when the non-Hermiticity parameter vanishes, i.e. $\delta = 0$.

As $\mathcal{H}$ respects the charge conjugation symmetry, eigenvalues come in pairs such that the set of all energies satisfy $\{\varepsilon\} = \{\varepsilon^*\}$. This implies that degeneracies of phases can be merely obtained by vanishing real parts of the spectrum. In a finite system, finite size effects will give rise to small splitting between degenerate states in the thermodynamic limit.

For finite models, it is thus convenient to define the quasi-degeneracy χ given by

$$\chi = \sum_{\alpha} e^{-\lambda|\varepsilon_\alpha - \varepsilon_0|} \tag{2}$$

with ε_α being the αth eigenvalue, and ε_0 the ground state [104]. The parameter λ controls the energy resolution of the quasi-degeneracy, which in the limiting case $\lim_{\lambda\to\infty}\lim_{L\to\infty}\chi$ becomes the thermodynamic degeneracy of the ground state [105]. We will focus our analysis on system sizes with $L = 16$, that are large enough to show different transition regimes that would converge to the different phases of the model in the thermodynamic limit.

In addition to the quasi-degeneracy χ, we can characterize the phase boundaries using the electronic correlation entropy given by [34, 106–110]

$$\mathcal{C}_{\rm corr} = -\frac{1}{L}\sum_{j=1}^{L} s_j \log(s_j), \tag{3}$$

where $0 \leqslant s_j \leqslant 1$ is the jth eigenvalue of the correlation matrix. The elements of the correlation matrix $C^{\rm mat}$ are two-point correlation functions that read $C^{\rm mat}_{ij} = |\det[\sum_{ll'}^{[\chi]} \rho_{ij}^{ll'}]|$ with $\rho_{ij}^{ll'} = \langle\Psi_l|c_i^\dagger c_j|\Psi_{l'}\rangle$, where Ψ_l is the lth eigenstate on the ground state manifold, and $[\chi]$ is the closest integer to χ. The correlation matrix $\mathcal{C}_{\rm corr}$ measures many-body entanglement and vanishes in systems described by Hartree–Fock product states [34, 111–114]. It is worth noting that while superconducting states can be represented as a product state in the Nambu basis, the previous definition of correlation entropy yields a finite value for superconducting states. Large values of $\mathcal{C}_{\rm corr}$ in certain regions of the phase diagram imply that the system cannot be represented by a Hartree–Fock product state.

3. Machine learning methodology

We now present the machine learning methodology to learn the different regimes of the interacting models, taking as target functions χ and $\mathcal{C}_{\rm corr}$. The input of our machine-learning algorithm corresponds to short-range many-body correlators in the form of two-point and four-point correlation functions given by

$$d_{ij} = \langle c_i^\dagger c_j\rangle_{[\chi]}, \quad f_{ij} = \langle c_i^\dagger c_j^\dagger\rangle_{[\chi]}, \tag{4}$$

$$k_{ij} = \langle \kappa_{ij}\kappa_{ij}^\dagger\rangle_{[\chi]}, \quad p_{ij} = \langle n_i n_j\rangle_{[\chi]}, \tag{5}$$

where $\kappa_{ij} = c_i c_j$ and $\langle\hat{A}\rangle_{[\chi]} \equiv |\det[\sum_{ll'}^{[\chi]} A_{ll'}]|$ with $A_{ll'} = \langle\Psi_l|\hat{A}|\Psi_{l'}\rangle$. Here, i,j run on four neighboring sites in the middle of the chain so that the algorithm relies solely on short-range correlation functions. These correlation functions are used to predict the quasi-degeneracy χ and the correlation entropy $\mathcal{C}_{\rm corr}$. We collect 20 000 different non-Hermitian interacting realizations on the $(U/t,\eta)$ plane, taking the non-Hermiticity parameter as $\delta \in \{0, 0.5\}$. To predict the quasi-degeneracy, we explore two strategies, the first one is based on transforming the task in a classification problem for $[\chi]$, and the second one is a regression problem for χ. The prediction of $\mathcal{C}_{\rm corr}$ is treated as a regression problem. The details of our NN architecture for each of these cases are presented in the supplemental materials (SM) [115].

4. Results

We now present the predictions of different regimes based on various correlators for our Hermitian and non-Hermitian limits. We start with the Hermitian phase diagram shown in figures 2(a) and (b). These panels present the numerical regimes obtained with the exact diagonalization method [116]. The finite-size effect pushed the regime crossovers to smaller η values from the phase boundaries in the thermodynamic limit, a feature that can be systematically analyzed using finite size scaling [93]. Performing this scaling gives rise to the thermodynamic phase boundaries shown in the cyan lines [93].

The associated predicted regime crossovers using χ are displayed in figures 2 (c)–(f). Here, we compare the true (figures 2 (a) and (b) and predicted (figures 2(c)–(f)) phase diagrams obtained from training the NN model using the two-point correlation functions (figures 2(c) and (d)) or the combination of both two-point and four-point correlation functions (figures 2(e) and (f)). The values of $[\chi]$ in figures 2(a), (c) and (e) are discrete, and the predicted results belong to different classes of $[\chi]$. In panels figures 2(b),(d) and (f), a regression architecture is used to predict χ, and the predicted results figures 2(d) and (f) are obtained as a regression problem.

We now examine how the regimes of the non-Hermitian interacting model can be deduced from short-range correlators using a model trained by the Hermitian dataset with $\delta = 0.0$, as shown in figure 3. Figures 3(c)–(f) shows the predicted phase crossovers obtained by the algorithm trained with Hermitian data, which should be compared with true outputs of the non-Hermitian problem shown in figures 3(a) and (b). Interestingly, the predicted results based on two-point correlation functions based on a classification architecture for $[\chi]$ (figure 3(c)) display a large discrepancy. Such inaccurate prediction is eliminated by incorporating four-point correlation functions into the considered observables, as shown in figure 3(e). We further note that if we phrase the task as a regression problem, as shown in figures 3(b), (d) and (f), the predicted phase boundaries based on training with two-point correlation functions are more reliable, as shown in figure 3(d). These results show that the quasidegeneracy of the non-Hermitian model can be extracted from a model trained purely on Hermitian data.

Aside from χ, the different regimes can be characterized using the correlation entropy $\mathcal{C}_{\rm corr}$ both in Hermitian $\delta = 0$ and non-Hermitian $\delta = 0.5t$ systems as respectively shown in figures 4(a) and (b). Finite-size effects are reflected in the deviations from the cyan lines, which are inherited by the changes of $[\chi]$ that impact the definition of the correlation entropy. Interestingly, $\mathcal{C}_{\rm corr}$ exhibits further transitions, quantitatively

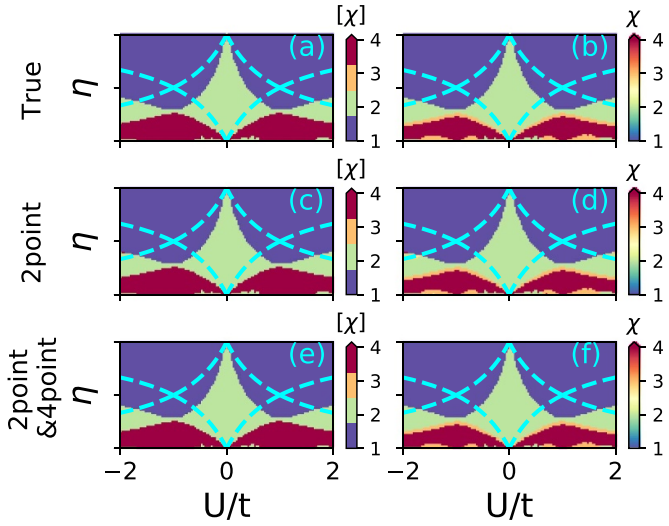

Figure 2. Hermitian interacting model: The phase diagram of the Hermitian many-body model with $L = 16$ on the $U/t - \eta$ plane at $\delta = 0.0$. The results in (a) and (b) are calculated by exact diagonalization. Panels (c), (d) use a machine learning architecture that uses solely two-point correlation functions as input. In contrast, panels (e), (f) use an architecture trained on both two-point and four-point correlation functions. The quasi-degeneracy in (c), (e) is treated as a discrete classifier for $[\chi]$, while it is treated as a regression problem in (d), (f). The boundaries in the thermodynamic limit are shown by cyan dashed lines.

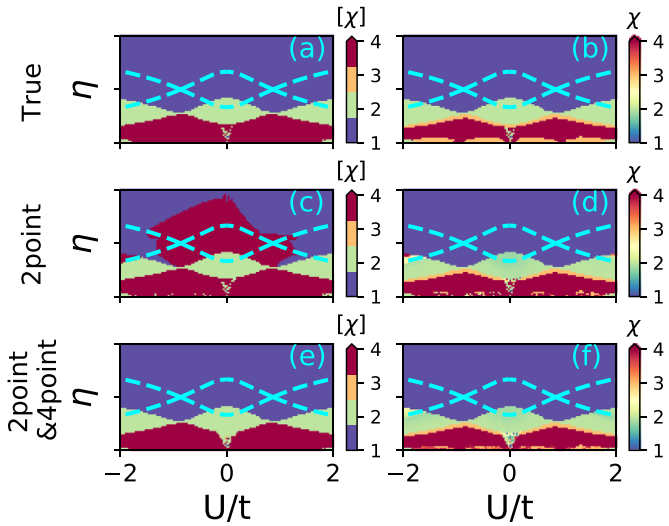

Figure 3. Non-Hermitian interacting model: the regimes of the non-Hermitian many-body model with $L = 16$ on the $U/t - \eta$ plane at $\delta = 0.5$. The results in (a) and (b) are calculated by exact diagonalization. The regimes in (c), (d) are obtained using architectures trained by two-point correlations, whereas (e), (f) are trained on both two-point and four-point correlation functions. The quasi-degeneracy in (c), (e) is treated as a discrete classifier for $[\chi]$, while it is treated as a regression problem in (d), (f). The boundaries in the thermodynamic limit are shown by cyan dashed lines and black dashed-dotted lines. It is observed that while two-point correlators fail to predict the non-Hermitian regimes in (c), the inclusion of four-point correlators recovers accurate regime crossovers (e).

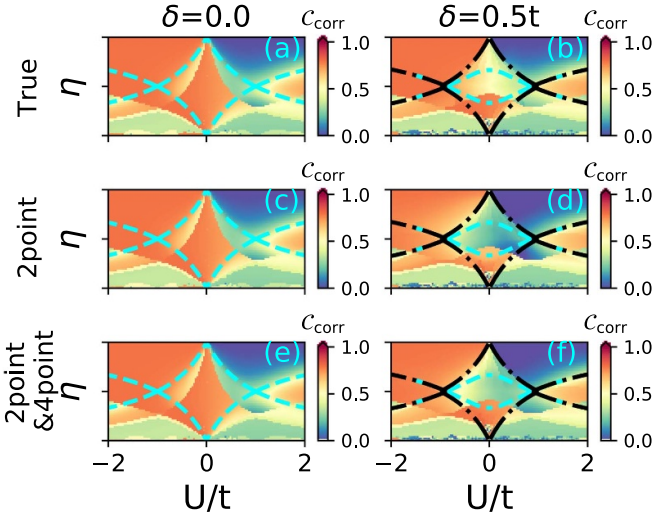

Figure 4. Correlation entropy predictions: the regimes of the non-Hermitian many-body model with $L = 16$ on the $U/t - \eta$ plane at $\delta = 0.0$ (a), (c), (e), $0.5t$ (b), (d), (f). The trained models are obtained using the Hermitian datasets with $\delta = 0.0$. The color bar denotes $\mathcal{C}_{\text{corr}}$. The regimes panels (c), (d) are obtained using the machine learning model trained by two-point correlation functions, whereas (e), (f) are trained on both two-point and four-point correlation functions. The boundaries in the thermodynamic limit given in the main text are shown by cyan dashed lines and black dashed-dotted lines.

described by the analytic phase boundaries. The absence of a finite size effect in different regions of the parameter space, delineated by the black dashed-dotted lines, signals the exponential convergence towards the ground state due to finite correlation gaps. Similar behavior is reported in Mott insulators [34, 117] and magnetic vortex liquids [118]. In figure 4, we present the various regimes for Hermitian (figures 4 (a), (c) and (e)) and non-Hermitian (figures 4(b), (d) and (f)) systems using a model trained on Hermitian models with only two-point (figures 4(c) and (d)) or the combination of two-point and four-point correlation functions (figures 4(e) and (f)). Overall, all the thermodynamic phase boundaries are qualitatively signaled by the correlation entropy. In the non-Hermitian cases, we can identify some regions, mainly inside the black diamond-like phase boundaries, featuring differences from the true results. These differences are reduced when including four-point correlation functions in the training of the Hermitian model; see also the SM [115]. It is worth noting that the regions with the most discrepancies have a topological superconducting nature, suggesting that phases with topological and many-body effects require higher-point correlation functions to be inferred with short-range information.

Our machine learning models trained only in Hermitian Hamiltonians can characterize the regimes of non-Hermitian interacting systems. Our results indicate that the model maintains its predictive accuracy across different parameter regions, showing the generalizability of our approach. It is

interesting to note that, while we observe a general agreement, small discrepancies between the machine learning predicted regimes and the computationally exact ones can be observed. This is because non-Hermitian many-body systems can show richer ground states than their Hermitian analog due to the extent of their spectrum in the complex plane. As a result, many-body wavefunctions in non-Hermitian models are genuinely different from their Hermitian counterparts, as these wavefunctions can span different regions of the Hilbert space beyond the original Hermitian training. Interestingly, this discrepancy opens the possibility of using our machine learning algorithms to directly identify non-Hermitian phases that do not have a Hermitian counterpart. Finding the smallest machine learning model to achieve our objective, developing a more interpretable algorithm [119, 120], and the possibility of domain adaptation from transfer learning [121, 122] are three potential future steps to enhance the performance of our algorithm. Pursuing domain adaptation would require fine-tuning the model with non-Hermitian data, which in turn requires actual knowledge of how the non-Hermitian phase diagram is. Our approach takes the perspective that no information about the non-Hermitian phase diagram is known, and only the Hermitian one is available for training. This approach emphasizes that even in the case in which no domain adaptation is done as in a situation in which no non-Hermitian data is available, a single shot transfer learning already provides valuable results. Our results provide a starting point for performing domain adaptation in non-Hermitian systems, and we hope that our manuscript will motivate further efforts in this direction.

5. Conclusion

To summarize, we have demonstrated a transfer machine learning methodology whereby training on Hermitian many-body models allows us to predict different regimes of interacting non-Hermitian quantum many-body models. Our algorithm effectively acts as a variational function that allows mapping the local correlators to the phase of the system. This opens the possibility of employing Hermitian many-body physics to understand the phase boundaries of non-Hermitian systems, leveraging solutions and methodologies currently only applicable to quantum many-body models. Our findings reveal that the prediction of quasi-degeneracy or correlation entropy allows the identification of different regions in interacting systems. Interestingly, these two methodologies are affected in a qualitatively different manner for finite-size effects, with the correlation entropy showing the fastest convergence to the thermodynamic limit. Our machine-learning methodology relies on short-range correlation functions, which open the possibility to potential deployments of our technique in experimental setups. Our results establish transfer learning as a promising strategy to map regimes on non-Hermitian quantum many-body models and to identify regimes featuring phenomena not observable in Hermitian models.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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