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Modeling drug combination effects via latent tensor reconstruction

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Abstract

Motivation: Combination therapies have emerged as a powerful treatment modality to overcome drug resistance and improve treatment efficacy. However, the number of possible drug combinations increases very rapidly with the number of individual drugs in consideration, which makes the comprehensive experimental screening infeasible in practice. Machine-learning models offer time- and cost-efficient means to aid this process by prioritizing the most effective drug combinations for further pre-clinical and clinical validation. However, the complexity of the underlying interaction patterns across multiple drug doses and in different cellular contexts poses challenges to the predictive modeling of drug combination effects.

Results: We introduce comboLTR, a highly time-efficient method for learning complex, non-linear target functions for describing the responses of therapeutic agent combinations in various doses and cancer cell-contexts. The method is based on a polynomial regression via powerful latent tensor reconstruction. It uses a combination of recommender system-style features indexing the data tensor of response values in different contexts, and chemical and multi-omics features as inputs. We demonstrate that comboLTR outperforms state-of-the-art methods in terms of predictive performance and running time, and produces highly accurate results even in the challenging and practical inference scenario where full dose–response matrices are predicted for completely new drug combinations with no available combination and monotherapy response measurements in any training cell line.

Availability and implementation: comboLTR code is available at https://github.com/aalto-ics-kepaco/ComboLTR.

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Supplementary information: Supplementary data are available at Bioinformatics online.

1 Introduction

Combination therapies, involving two or more drugs, offer several advantages over standard monotherapies, including higher treatment efficacies and overcoming resistance mechanisms by modulating multiple targets and signaling pathways. This is especially important in combating complex multi-factorial diseases, such as cancer, and cardiovascular, neurological and autoimmune disorders. Moreover, drugs in combination can often be administered in lower individual doses which, in turn, results in reduced risk of adverse reactions (Al-Lazikani et al., 2012; Pemovska et al., 2018). The number of US Food and Drug Administration-approved drug combinations has been continuously growing since the first approvals for co-administration of drugs to treat nervous and respiratory system disorders in 1940s (Das et al., 2018). Currently, most of the ongoing research and development is focused on combinatorial therapies for different cancer types (Pemovska et al., 2018). The development is, however, very challenging as the number of possible pairwise combinations increases very rapidly with the number of individual drugs, not even mentioning the enormous size of the chemical universe that could be explored (Reymond and Awale, 2012).

Computational approaches offer cost-effective means for large-scale, fast and systematic pre-screening and prioritization of potential drug combinations for further experimental validation. Most of the machine-learning models introduced to date and benchmarked in crowd-sourced DREAM Challenge competitions (Bansal et al., 2014; Menden et al., 2019) focus directly on the prediction of synergistic drug combinations (Li et al., 2019; Preuer et al., 2018; Sidorov et al., 2019; Tonekaboni et al., 2018; Yang et al., 2020). Nonetheless, modeling the full dose–response matrices of drug pairs offers more in-depth view of their complex response landscapes, and allows to calculate different synergy metrics as a follow-up step. This is important especially for translational applications, where knowledge of optimal dose combination regions is often critical (Janevski et al., 2020; Yang et al., 2015).

Here, we introduce comboLTR, a new polynomial regression-based framework for modeling anti-cancer effects of drug combinations in various doses. We compare the performance of comboLTR...
to random forest (RF) and recently introduced method by our groups, the comboFM method (Julkunen et al., 2020), using the National Cancer Institute (NCI)-ALMANAC dataset (Holbeck et al., 2017) generated by the US NCI. Both comboLTR and comboFM exploit the fact that dose–response matrices of drug combinations present challenges. An arbitrary multivariate polynomial function learning power, capable of accurately representing continuous functions with a fixed $L_\infty$ norm-based tolerance. This fact allows us to exploit the Stone-Weierstrass theorem and its generalizations (Prenter, 1970) to approximate those functions by polynomials on a compact subset with an accuracy not worse than a given arbitrary small error.

However, estimating high-degree multivariate polynomial functions presents challenges. An arbitrary multivariate polynomial defined on the field of real numbers can be described by \( \binom{N + d}{n} \) parameters, where \( n \) is the number of variables, and \( n_d \) is the maximum degree of the polynomial. Thus, the complexity relating to the size of the underlying parameter tensor is \( O(n^m) \), which grows exponentially in the number of parameters.

This exponential complexity in the polynomial degree presents both statistical and computational challenges: there is often not enough data to reliably estimate all the coefficients, and the exponential time and space complexity forbids processing sufficiently large training sets.

The key approach to tackle this exponential complexity in higher-order factorization machines (HOFM) (Blondel et al., 2016; Rendle, 2010) is a special representation of the coefficients as inner products of factors: e.g. for the second order terms

\[
w_{i_{1}...i_{d}} = \langle p_{i_{1}}, p_{i_{2}} \rangle = \sum_{j=1}^{m} p_{i_{1},j} p_{i_{2},j},
\]

where \( p_j \in \mathbb{R}^m \) encodes the participation of \( i \)th variable in \( n_t \) factors. For higher degree terms, the same is given by a generalized inner product.
$w_{n_1...n_d} = (p_1 ... p_n) = \sum_{i=1}^{n} p_{i1} ... p_{in_d}$.

This factorized representation drastically reduces the number of parameters to $O(n_1 \cdot n_2 \cdot \ldots \cdot n_d)$ (Blondel et al., 2016). The HOFM was recently demonstrated to be able to accurately predict drug combination responses (Julkunen et al., 2020). However, HOFMs are constrained to symmetric polynomials, i.e. functions that are invariant to permutation of features, which restricts the HOFM model as a general regression model.

In this work, we follow an alternative approach for factorizing the parameter representation, called LTR (Szedmak et al., 2020), that starts from the full-order tensor representation of the unknown regression coefficients and learning a factorization into rank-one tensors (of full order) that optimizes the regression error (Table 1). Importantly, the LTR model lifts the limitation of symmetricity of the learned polynomial, and can therefore tackle a wider class of learning problems.

### 2.4 Tensor-based representation of polynomial functions

A polynomial function over the real numbers with degree $n_d$ and with $n$ variables can also be written in a compact form

$$
\pi(x) = (T, x) \otimes_{d=1}^{n_d} x,
$$

where $T$ is a symmetric tensor of order $n_d$ and with dimension $x_{d=1}^{n_d}$. If the vector $x$ is given in homogenous form, extended with a constant 1, then (2) covers all possible polynomials up to degree $n_d$. The tensor $T$ can be given in a decomposed HOSVD form (Kolda and Bader, 2009; Lathauwer et al., 2000),

$$
T = \sum_{i=1}^n a_i \otimes_{d=1}^{n_d} p_i^{(d)}
$$

s.t. $||p_i^{(d)}|| = 1, p_i^{(d)} \in \mathbb{R}^n, t \in [n_d].$

This representation is generally not unique, see Lathauwer et al. (2000) and de Silva and Lim (2008). By replacing $T$ with its decomposed form, the polynomial function turns into the following expressions

$$
\pi(x) = \sum_{i=1}^n a_i (\otimes_{d=1}^{n_d} p_i^{(d)}, \otimes_{d=1}^{n_d} x) = \sum_{i=1}^n a_i \prod_{d=1}^{n_d} (p_i^{(d)}, x),
$$

where we exploit the well-known identity connecting the inner products and the tensor products (Golub and Loan, 2013). This form only consists of terms of scalar factors, where each scalar is the value of a linear functional acting on the space $X$. This transformation eliminates the difficulties, which arise in working directly with full tensors. Observe that the function $\pi$ is linear in each of the vector-valued parameters, $p_i^{(d)}, t \in [n_d], d \in [n_d].$

We can further transform the polynomial representation (2.4) into a form, which does not contain any reference to tensor product. We have a following simple statement, which allows us to introduce an additional factorization within the polynomial function to reduce further the number of parameters.

Proposition 1. The polynomial function $\pi(x)$ can be expressed only by the help of matrix and pointwise, Hadamard, products, namely

$$
\pi(x) = \sum_{i=1}^n a_i \prod_{d=1}^{n_d} (p_i^{(d)}, x) = \lambda^T c_{d=1}^{n_d} p^{(d)} x,
$$

where $p^{(d)}$ is a matrix of size $n_1 \times n$ for any $d$, whose rows are given as $p_i^{(d)} = p_i^{(d)}$, and $\lambda$ is a vector with components $\lambda_i, t \in [n_d]$.

Proof. The matrix-vector product $p^{(d)} x$ yields a vector with components $(p_i^{(d)} x_1, \ldots, p_i^{(d)} x_n)$, and after a rearrangement, the original form can be restored. \hfill \square

### 2.5 LTR—basic form

**comboLTR** is built upon the LTR-based polynomial regression method (Szedmak et al., 2020). LTR exploits the representation shown in Proposition 1, which leads to the following optimization problem:

$$
\min \frac{1}{mn_y} \sum_{i=1}^m ||y_i - (\otimes_{d=1}^{n_d} p_i^{(d)} x_i))DQ||^2 + C_p \frac{\|p_i^{(d)}\|^2}{n_1 n_2 \ldots n_d} + C_p \frac{|Q|^2}{n_1 n_2 \ldots n_d}
$$

w.r.t. $\lambda, Q, p^{(d)}, d \in [n_d],$

where $C_p$ and $C_p$ are penalty constants, and matrix $Q$ projects the vector given by the polynomial function of dimension $n_1$ into the output space.

### 2.6 Reparametrization of the polynomial representation

In the LTR model, the predictor is implemented via a polynomial function $\pi$ acting on vectors $x$ of dimension $n$. The parameter space corresponding to matrices $p^{(d)}, d \in [n_d]$ has dimension $n_1 n_2 \ldots n_d$ which is large enough to fit the polynomial to a non-linear function with complex structure, but it requires a large sample to achieve a proper estimation of those parameters. The LTR framework can be extended to increase the flexibility, and in the same time, to reduce the dimension of the parameter space. To this end, let the polynomial function of (4) be reformulated

$$
\pi(\phi(x)) = \sum_{i=1}^n a_i \prod_{d=1}^{n_d} (\phi_t^{(d)} A(U^{(d)} x)) = \phi^T c_{d=1}^{n_d} V^{(d)} A(U^{(d)} x),
$$

where $A$ is a pointwise activation function, and the matrix $U^{(d)}$ is a linear transformation projecting the original input vector into a space with lower dimension, $n_k$, for each $d \in [n_d]$. That projection can enforce a bottleneck within the polynomial function. This modification preserves the linear dependence on the matrix valued parameters. The expression $\phi(x) = A(U^{(d)} x)$ might be viewed as a layer of a neural network. The main difference is that the layers within the LTR are joined by a polynomial function in a parallel way instead of being connected sequentially.

The following table summarizes the matrices describing the extended LTR problem.

<table>
<thead>
<tr>
<th>Polynomial parameters</th>
<th>$V^{(d)}$</th>
<th>$d \in [n_d]$</th>
<th>$\mathbb{R}^{n_1 \times n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output projection</td>
<td>$Q$</td>
<td>$\mathbb{R}^{n_1 \times n_2 \ldots n_d}$</td>
<td></td>
</tr>
<tr>
<td>Scaling</td>
<td>$D_\lambda = \text{diag}(\lambda)$</td>
<td>$\mathbb{R}^{n_1 \times n}$</td>
<td></td>
</tr>
<tr>
<td>In layers projection</td>
<td>$U^{(d)}$</td>
<td>$d \in [n_d]$</td>
<td>$\mathbb{R}^{n_1 \times n_k}$</td>
</tr>
<tr>
<td>scaling value</td>
<td>$D_\lambda^{(d)} = \text{diag}(\lambda^{(d)})$</td>
<td>$\mathbb{R}^{n_1 \times n}$</td>
<td></td>
</tr>
<tr>
<td>$A^{(d)} = A(XD_\lambda^{(d)} U^{(d)})$</td>
<td>$U^{(d)}$</td>
<td>$U^{(d)}$</td>
<td>$\mathbb{R}^{n_1 \times n_k}$</td>
</tr>
<tr>
<td>Full polynomial</td>
<td>$F$</td>
<td>$\mathbb{R}^{n_1 \times n_1 \ldots n_d}$</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>$E$</td>
<td>$\mathbb{R}^{n_1 \times n_1 \ldots n_d}$</td>
<td></td>
</tr>
</tbody>
</table>

The parameter $\lambda$ corresponds to the singular values of the tensor decomposition, see in (3).
The optimization problem of (7) is solved by an iterative algorithm, where
\[
\min \frac{1}{2m_{\delta}} \| Y - FD_{\delta}Q \|_F^2 + \frac{C_{\delta}}{2n_{\delta}} \| \lambda \|_2^2
\]
\[
\text{w.r.t.} \quad U^{(\delta)}, \lambda^{(\delta)}, V^{(\delta)}, Q, d = [n_{\delta}],
\]
\[
\text{s.t.} \quad \| U^{(\delta)} \|_2 = 1, \quad ||\lambda^{(\delta)}||_2 = 1,
\]
\[
\| V^{(\delta)} \|_2 = 1, \quad ||Q||_2 = 1,
\]
\[
j \in [n], \quad t \in [n_{\delta}], \quad d \in [n_{\delta}],
\]
where \( C_{\delta} \) is a penalty constant relating to the scale factor \( \lambda \).

2.7 Projection-based algorithm

The optimization problem of (7) is solved by an iterative algorithm, which maintains the constrains imposed on the rows of parameter matrices by projecting them onto the unit sphere.

- **Step 1** Let \( \ell = 0 \), and the learning speed be \( 0 < \gamma < 1 \).
- **Step 2** Initialize the parameters
  \[
  \lambda^{(\delta)}[t] = 1_n, \quad \lambda'[t] = 1_n,
  \]
  \[
  U^{(\delta)}[t], V^{(\delta)}[t] \sim N(0,1),
  \]
  \[
  Q[d] \sim N(0,1),
  \]
  \[
  d \in [n_{\delta}], \quad t \in [n_{\delta}], \quad s \in [n_{\delta}],
  \]
  where \( N(0,1) \) is the standard normal distribution.
- **Step 3** Normalize the rows of the optimization parameters by \( L_2 \) norm. Only the vector \( \lambda'[t] \) will be unnormalized.
- **Step 4** Set the scale value for the unnormalized vector \( \lambda \) by assuming that all other parameters are fixed. Compute
  \[
  F[t] = C_{\delta}^d A(XD_{\delta}U^{(\delta)}[t])V^{(\delta)}[t]^T
  \]
  and solve the linear least square problem for \( \lambda'[t] \)
  \[
  \min_{\lambda'[t]} \| Y - F[t]D_{\delta}Q[d] \|_2^2.
  \]
- **Step 5** Compute the value of the objective function of the extended LTR problem given by (7)
  \[
  h^{(\delta)}[t] = \| Y - F[t]D_{\delta}Q[d] \|_2^2.
  \]
- **Step 6** Compute the partial gradients of \( h^{(\delta)} \) by applying (15),
  \[
  \nabla_{U^{(\delta)}} h^{(\delta)}, \nabla_{V^{(\delta)}} h^{(\delta)}, d \in [n_{\delta}].
  \]
- **Step 7** Update the parameters
  \[
  \lambda^{(\delta)}[t + 1] = \lambda^{(\delta)}[t] + \gamma \nabla_{\lambda^{(\delta)}} h^{(\delta)}[t],
  \]
  \[
  \lambda'[t + 1] = \lambda'[t] + \gamma \nabla_{\lambda'[t]} h^{(\delta)}[t],
  \]
  \[
  U^{(\delta)}[t + 1] = U^{(\delta)}[t] + \gamma \nabla_{U^{(\delta)}} h^{(\delta)}[t], d \in [n_{\delta}],
  \]
  \[
  V^{(\delta)}[t + 1] = V^{(\delta)}[t] + \gamma \nabla_{V^{(\delta)}} h^{(\delta)}[t], d \in [n_{\delta}],
  \]
  \[
  Q[d] = Q[d] + \gamma \nabla_{Q[d]} h^{(\delta)}[t].
  \]
- **Step 8** Normalize the optimization parameters in \( L_2 \) norm.
- **Step 9** \( \ell = \ell + 1 \).
- **Step 10** Go to Step 5.

For large-scale applications, the above algorithm is further extended by partitioning the training examples into mini-batches, and processing them sequentially. A single run of the cycle based on mini-batches is taken as an epoch, and repeated. To reduce the variance caused by the partition, a momentum-based update can be applied, e.g. Nesterov Accelerated Gradient method, or the ADAM method frequently applied for Deep Neural Networks (Kingma and Ba, 2015; Nesterov, 2005; Polyak, 1964).

2.7.1 Gradients

Let the matrix \( H^{(d)} \in \mathbb{R}^{m_{\delta} \times n_{\delta}} \) contain the partial derivatives of the activation function with respect to the components of the matrix \( XD_{\delta}U^{(d)} \), where we exploited that the activation function is a pointwise map of the matrix in its argument. We exploit the following expressions to shorten the gradient formulas

\[
F_{i,d} = c_{i,d}^n A^{b} \lambda_{d}^T
\]
\[
B^{(d)} = EQ^T \cdot F_{i,d}
\]
\[
C^{(d)} = X^T (B^{(d)} - \lambda_{d}^T) H^{(d)}
\]
Then, the gradients are expressed in a compact form

\[
\nabla_{U^{(\delta)}} h^{(\delta)}[t] = \frac{1}{m_{\delta}} \sum_{d=1}^{m_{\delta}} \left( C^{(d)} \bullet U^{(\delta)} \right) 1_{n_{\delta}}
\]
\[
\nabla_{V^{(\delta)}} h^{(\delta)}[t] = \frac{1}{m_{\delta}} \sum_{d=1}^{m_{\delta}} \left( C^{(d)} \bullet \lambda'[t] 1_{n_{\delta}} \right)
\]
\[
\nabla_{Q[d]} h^{(\delta)}[t] = \frac{1}{m_{\delta}} \sum_{d=1}^{m_{\delta}} \left( F_{i,d} \cdot EQ^T \right) 1_{n_{\delta}} + C_{d} \lambda_{d}.
\]
\[
\nabla_{Q[d]} h^{(\delta)}[t] = \frac{1}{m_{\delta}} \sum_{d=1}^{m_{\delta}} \left( F_{i,d} \cdot EQ^T \right) 1_{n_{\delta}} + C_{d} \lambda_{d}.
\]

2.8 Dataset

In order to evaluate the performance of comboLTR, we used the drug combination responses in human cancer cell lines from the NCI-ALMANAC study (Holbeck et al., 2017). To exploit more data sources, especially multi-omics profiles of the cancer cell lines, we filtered the data to include only the cell lines for which gene expression, CNV, CRISP-Cas9 gene knock-outs and proteomics data were available. The resulting dataset consisted of 828 324 response measurements of 5035 drug combinations and 15 396 monotherapies in 19 cancer cell lines originating from 9 tissue types. Each drug combination has been screened using 4 \times 4 dose–response matrix design. The response measurements are given in the form of percentage growth of the cell lines with respect to a control. The distribution of our drug combination response dataset in 19 cell lines was identical to the distribution of all drug combination responses from the NCI-ALMANAC study, as shown in Supplementary Figure S1.
3 Results

We evaluated the performance of comboLTR in four practical prediction scenarios (Fig. 2):

- **Filling in the gaps in partially measured dose–response matrices (S1).**
- **Prediction of complete dose–response matrices of new drug combinations with no available combination response measurements in any cell line, monotherapy response values present for both drugs (S2).**
- **Prediction of complete dose–response matrices of new drug combinations with no available combination and monotherapy response measurements in any cell line (S3).**

Based on the results by Julkunen et al. (2020), predicting dose–response matrices of completely new drug combinations is the most challenging task from the above. Thus, we aimed to test our comboLTR framework under the difficult prediction scenario S2, and furthermore, under even more challenging prediction scenario S3. As shown in Figure 2, S3 has the least information available for a drug combination, since even monotherapy responses of single drugs are not present. Scenario S1 forms a relatively easy task, and thus it was considered as the reference prediction scenario. For completeness, in addition to these three scenarios, following Julkunen et al. (2020), we also considered the scenario of predicting dose–response matrices of previously untested drug–drug–cell line triplets in the case where the response matrices of the same drug combination in other cell lines are known. However, as it was not our main focus in this study, the results for this prediction scenario are included in the Supplementary material only (Supplementary Tables S1 and Fig. S2). We also benchmarked the performance of comboLTR against RF and comboFM.

### 3.1 Model optimization via 5-fold cross validation

We applied 5-fold cross validation (CV) in all prediction scenarios in order to tune the model parameters and evaluate the predictive performance. In scenario S1, for each dose–response matrix, combination responses were randomly selected into test sets. In scenario S2, dose–response matrices of certain drug combinations in all cell lines were randomly selected into test sets. All monotherapy responses were kept in the training sets for S1 and S2 prediction scenarios. S3 is similar to S2 but with all monotherapy responses excluded from the training set.

Based on our previous research, the degree of the polynomial function in comboLTR was set to five to model the interactions between the five components, i.e. two drugs, their concentrations and the cell line, which uniquely determine each drug combination response in the drug combination response tensor. A total of 20 drugs were randomly selected to subsample the full dataset for comboLTR parameter tuning. The subsampled dataset contained 31 095 response measurements of 208 drug combinations and 1901 monotherapies in 19 cell lines. The subsampled drug combination responses had almost identical distribution as our full dataset and also the whole dataset from NCI-ALMANAC study (Supplementary Fig. S1). Once parameters were determined, the performance of the model was evaluated using 5-fold CV on the full dataset, with the exception that the subsampled dataset was present in the training set only. comboLTR was evaluated using 5-fold CV for up to the 9th order with rank 200. Only very slight overfitting was observed in the highest order models.

We used a python implementation of RF from scikit-learn (Pedregosa et al., 2011) and its default parameters for training and prediction. Parameters for comboFM were taken from the original publication (Julkunen et al., 2020). In addition to fully evaluate the predictive performance of comboLTR and RF, in the most challenging prediction scenario S3, their parameters were also optimized using the subsampled drug combination responses. The models with optimal parameters were then applied on the full dataset in the prediction scenario S3.

### 3.2 Prediction of anti-cancer effects of drug combinations

We used different feature combinations to train comboLTR model, as shown in Table 2. Since the one-hot encoded tensor indices are only positional features of the quintuplets, MACCS fingerprint and multi-omics data were used as auxiliary features to provide additional information on drugs and cell lines. In scenario S1, when filling in the gaps in partially measured dose–response matrices, the performance difference between feature combinations was negligible. Using only tensor index features resulted in the Pearson correlation between predicted and measured responses of 0.915, whereas adding auxiliary chemical and biological features led to the Pearson correlation of 0.922. However, in scenarios S2 and S3, when predicting the responses of completely new drug combinations, even without monotherapy responses present, adding auxiliary features clearly increased the prediction performance. In particular, in the most challenging scenario S3, using tensor indices only and additionally including auxiliary features, resulted in the Pearson correlations of 0.893 and 0.915, respectively. With the advantage of handling large feature vectors, comboLTR can harness data from different sources for the improved prediction performance. Thus, tensor index features, chemical and multi-omics auxiliary features were used in all further experiments.
Table 2. Performance of comboLTR, comboFM and RF under different prediction scenarios and using different features

<table>
<thead>
<tr>
<th>Features</th>
<th>Method</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensor indices</td>
<td>comboLTR</td>
<td>0.915 ± 0.009</td>
<td>0.894 ± 0.002</td>
<td>0.883 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>comboFM</td>
<td>0.920 ± 0.010</td>
<td>0.914 ± 0.003</td>
<td>0.907 ± 0.004</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>0.886 ± 0.019</td>
<td>0.853 ± 0.010</td>
<td>0.858 ± 0.010</td>
</tr>
<tr>
<td>Tensor indices + MACCS</td>
<td>comboLTR</td>
<td>0.921 ± 0.010</td>
<td>0.908 ± 0.003</td>
<td>0.910 ± 0.003</td>
</tr>
<tr>
<td></td>
<td>comboFM</td>
<td>0.923 ± 0.012</td>
<td>0.923 ± 0.005</td>
<td>0.913 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>0.921 ± 0.016</td>
<td>0.872 ± 0.009</td>
<td>0.894 ± 0.005</td>
</tr>
<tr>
<td>Tensor indices + multi-omics</td>
<td>comboLTR</td>
<td>0.908 ± 0.014</td>
<td>0.909 ± 0.007</td>
<td>0.911 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>comboFM</td>
<td>0.910 ± 0.027</td>
<td>0.904 ± 0.014</td>
<td>0.870 ± 0.064</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>0.895 ± 0.019</td>
<td>0.859 ± 0.010</td>
<td>0.865 ± 0.010</td>
</tr>
<tr>
<td>Tensor indices + MACCS + multi-omics</td>
<td>comboLTR</td>
<td>0.922 ± 0.011</td>
<td>0.914 ± 0.006</td>
<td>0.915 ± 0.005</td>
</tr>
<tr>
<td></td>
<td>comboFM</td>
<td>0.915 ± 0.012</td>
<td>0.889 ± 0.024</td>
<td>0.878 ± 0.064</td>
</tr>
<tr>
<td></td>
<td>RF</td>
<td>0.923 ± 0.015</td>
<td>0.873 ± 0.009</td>
<td>0.896 ± 0.005</td>
</tr>
</tbody>
</table>

Note: Pearson correlations between predicted and measured drug combination responses, reported as averages across five CV folds ± SDs.

We used RF and comboFM as comparison methods in all prediction scenarios. Scatter plots of the predicted and measured drug combination responses are shown in Figure 3. As expected, in scenario S1, all three methods achieved comparable prediction performance. Pearson correlations for comboLTR, comboFM and RF were 0.922, 0.915 and 0.923, respectively. However, the difference in the performance of the methods became clearly visible in the most challenging and practical scenarios of predicting dose–response matrices of completely new drug combinations with and without monotherapy responses available (S2 and S3). Notably, under scenario S3, comboLTR, with a Pearson correlation of 0.915, clearly outperformed comboFM and RF (Pearson correlations of 0.878 and 0.896, respectively). It demonstrates that monotherapies play an important role in predicting higher-order interactions by comboFM. On the other hand, comboLTR produced more accurate predictions with fewer experimental measurements, which makes comboLTR more practical and applicable in recommending combination therapies.

To further study the prediction performance of those three methods, we investigated Pearson correlations for drug pairs in different drug classes and cell lines from different tissue types (Fig. 4). In general, comboLTR showed higher average Pearson correlation in most tissue types and drug classes. It was also corroborated by the violin plots that comboLTR shows better and more stable prediction performance across different drug classes and tissue types, particularly in the more challenging scenarios S2, and even S3 where less information was available.

Next, we evaluated the performance of the methods in quantifying the level of synergy and identifying highly synergistic drug combinations based on the predicted dose–response matrices. To calculate the synergy scores, we applied the NCI ComboScore introduced along with the NCI-ALMANAC dataset (Holbeck et al., 2017). Scatter plots and Pearson correlations between the NCI ComboScores calculated based on the complete measured and predicted dose–response matrices of the three methods are shown in Supplementary Figure S3. RF performed particularly well in the simplest scenario S1, but comboLTR clearly outperformed the other two methods in the more challenging scenarios, e.g. with a Pearson correlation of 0.67 compared to 0.57 (comboFM) and 0.46 (RF), in the S3 scenario. We also conducted discrimination analyses using the precision-recall (PR) curves (Supplementary Fig. S4) and receiver operating characteristic curves (Supplementary Fig. S5) to further evaluate the model performance in classifying drug combinations as synergistic versus non-synergistic with varying thresholds for synergy, in the three prediction scenarios. comboLTR showed very competitive performance in discriminating highly synergistic drug combinations across several top-% synergy thresholds in the most challenging prediction scenarios. For example, in scenario S3, the area under the PR curve at a synergy threshold of 5% for comboLTR, comboFM and RF were 0.25, 0.16 and 0.12, respectively (Supplementary Fig. S4).

To investigate the importance of multi-omics features, contribution of each type of omics data to the model performance was evaluated by ‘leave one type of omics data out’ and ‘adding only one type of omics data’ 5-fold CVs (Table 3). First, from the feature set comprising tensor indices, MACCS fingerprints and multi-omics data, each type of omics data were excluded to test their contribution to the predictive performance. Then, the predictive performance was also evaluated by including each type of omics data into the feature set, on top of tensor indices and MACCS fingerprints. The prediction performance was relatively stable when including or excluding certain types of omics data.

To investigate the importance of individual features, after the model was trained, each feature column was randomly permuted 20 times, and the average Pearson correlation difference between the models with original and permuted feature matrices was calculated as a measure to evaluate individual feature contribution to the predictive performance (Supplementary Fig. S6.). Weights of features from trained comboLTR model were also extracted and plotted in the form of a heatmap of L2-norm of each feature set, including MACCS fingerprints, gene expression, CNV, CRISPR-Cas9 gene knock-outs and proteomics data (Supplementary Fig. S6). In general, the most weight has been placed on tensor indices, while MACCS fingerprints and multi-omics data had only a relatively minor contribution to the model accuracy.

4 Discussion

Drug combinations are emerging as a powerful treatment modality to combat complex multi-factorial disorders, including cancer. Machine-learning models can significantly speed-up the search for effective drug combination therapies by systematically prioritizing the most promising combinations for further experimental validation. Using existing drug combination response data, we developed comboLTR to efficiently recommend combination therapies for cancer. Table 2 shows that comboLTR produces accurate and stable predictions even without monotherapy responses present in the training data. Monotherapy responses, which contain individual drugs tested in different cancer cell lines in various concentrations, are also costly and time-consuming to obtain in the lab. Without such limitation, comboLTR is more applicable and practical, especially in clinical research.

We compared the performance of comboLTR to RF and recently introduced comboFM method. Both comboLTR and comboFM are based on polynomial regression. A performance difference between the two methods in prediction scenario S3, where dose–response matrices of completely new drug combinations without monotherapy responses are inferred, could be due to different forms of polynomial functions to be learned. In comboLTR, a complete polynomial of degree n_y is used, while in comboFM, it is restricted to the symmetric polynomials. Since the monotherapies induce asymmetry in the drug representation, a
method which can cover the full range of possible polynomials has higher probability to combine both the symmetric and asymmetric relations. The symmetry restriction of comboFM also eliminates the monomials with higher-order occurrences of the polynomial variables, which could also reduce further the range of functions to be approximated. Thus, it could be hypothesized that comboFM mainly relies on lower-order interactions, such as monotherapy responses. The lack of such lower-order interaction information results in a performance drop of comboFM in the prediction scenario S3. We note that comboFM is a bit more competitive without using the MACCS and multi-omics features than when using them, which may be at least in part caused by the symmetricity of the polynomials with respect to the variables. Specifically, the tensor indices and the MACCS and multi-omics features are treated alike by comboFM, but not comboLTR. Tensor indices, however, do not allow any explanation of the predictions in terms of underlying biological functions or processes, and hence models relying solely on them might not be preferable in practical use.

Furthermore, in practical clinical applications, identification of synergistic drug combinations is of high interest. Importantly, comboLTR outperformed comboFM and RF in the most challenging prediction scenarios also in the task of discriminating highly synergistic drug combinations based on the predicted complete dose–response matrices and when using a range of different top-% synergy thresholds (Supplementary Figs S4 and S5).

Since CV experiments were run on different machines, the longest running time and median memory across all prediction scenarios were recorded (Table 4). Compared to comboFM, which also learns from higher-order interactions, comboLTR is significantly more time-efficient, especially in handling large feature vectors (Table 4). When training models using the full dataset with tensor index features, MACCS fingerprints and multi-omics information, only 3.1 h were needed for a 5-fold CV using comboLTR, whereas comboFM took 39 h. Most of the memory was used for storing the data.
In this work, genomic, transcriptomic and proteomic data were used to provide additional information on cancer cell lines. The complex interactions among and within multiple layers of omics were studied. The following sections detail the predictive performance of different models across tissue types and drug classes in three drug combination response prediction scenarios.

**S1: Filling in the gaps in partially measured dose-response matrices**

![Violin plots for tissue type correlations](image)

**S2: Predicting dose-response matrices of new drug combinations**

![Violin plots for drug class correlations](image)

**S3: Predicting dose-response matrices of new drug combinations w/o monotherapy responses**

![Violin plots for drug class correlations](image)

**Fig. 4.** Predictive performance of comboLTR, comboFM and RF across tissue types and drug classes in three drug combination response prediction scenarios. Violin plots were used to characterize Pearson correlations of predicted and measured drug combination responses across tissue types (a–c) and drug classes (d–f). Note that the order of tissue types and drug classes in the legends corresponds to their order in the violin plots.

**Table 3.** The 5-fold CV results of comboLTR, in the form of Pearson correlations, when leaving one type of omics data out or including only one type of omics data, compared with using the full multi-omics data, on top of tensor indices and MACCS fingerprints.

<table>
<thead>
<tr>
<th>Multi-omics feature combination</th>
<th>comboLTR</th>
<th>comboFM</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full multi-omics</td>
<td>0.922</td>
<td>0.914</td>
<td>0.915</td>
</tr>
<tr>
<td>Excluding gene expression</td>
<td>0.921</td>
<td>0.912</td>
<td>0.914</td>
</tr>
<tr>
<td>Excluding CNV</td>
<td>0.921</td>
<td>0.916</td>
<td>0.914</td>
</tr>
<tr>
<td>Excluding CRISPR knock-out</td>
<td>0.921</td>
<td>0.914</td>
<td>0.913</td>
</tr>
<tr>
<td>Excluding proteomics</td>
<td>0.920</td>
<td>0.911</td>
<td>0.914</td>
</tr>
<tr>
<td>Using only gene expression</td>
<td>0.921</td>
<td>0.912</td>
<td>0.911</td>
</tr>
<tr>
<td>Using only CNV</td>
<td>0.921</td>
<td>0.911</td>
<td>0.910</td>
</tr>
<tr>
<td>Using only CRISPR knock-out</td>
<td>0.921</td>
<td>0.909</td>
<td>0.911</td>
</tr>
<tr>
<td>Using only proteomics</td>
<td>0.921</td>
<td>0.910</td>
<td>0.910</td>
</tr>
</tbody>
</table>

**Table 4.** The time (h) and memory (GB) usage of comboLTR, comboFM and RF in 5-fold CV.

<table>
<thead>
<tr>
<th>Features</th>
<th>comboLTR</th>
<th>comboFM</th>
<th>RF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensor indices</td>
<td>1.1/24</td>
<td>1.2/20</td>
<td>1.2/24</td>
</tr>
<tr>
<td>Tensor indices + MACCS</td>
<td>2.1/35</td>
<td>5.9/35</td>
<td>0.4/38</td>
</tr>
<tr>
<td>Tensor indices + multi-omics</td>
<td>3.2/44</td>
<td>31.5/63</td>
<td>5.6/54</td>
</tr>
<tr>
<td>Tensor indices + MACCS + multi-omics</td>
<td>3.1/74</td>
<td>39.0/73</td>
<td>2.1/74</td>
</tr>
</tbody>
</table>

In this work, genomic, transcriptomic and proteomic data were used to provide additional information on cancer cell lines. The complex interactions among and within multiple layers of omics...
measures form a comprehensive molecular network. For example, CNVs affect expression of genes which, together with post-translational modifications, influence the quantity of proteins. Since the full multi-omics dataset included over 70,000 features, we reduced the dimensionality of the data by selecting only 1% of each type of omics data as auxiliary descriptors characterizing cell lines (see Section 2.7).

As shown together in Tables 2 and 3 and Supplementary Figure S6, the performance increase brought by integrating multi-omics data into the model was only modest. This phenomenon could be due to that only 1% of the full multi-omics dataset was taken into account, which represented only a small part of the cell's characteristics. Besides, the complex interactions of the molecular network were not taken into consideration in this experiment. For example, different drugs at various concentrations may result in multiple perturbations to the molecular network, which will change the cellular phenotype into diverse states. The lack of integrating such complicated interactions could lead to less relevant features selected for predicting drug combination responses. One of our future aims is to select cell features based on their connections with tested drug combinations, e.g. to assign weights to features based on their interaction strength with drugs.

On the other hand, MACCS fingerprint had slightly higher associated feature weights and performance increase, when compared to the multi-omics features. MACCS fingerprint characterizes drugs by the presence or absence of specific chemical substructures. As shown in Supplementary Figure S7, different drugs in our dataset have common substructures due to the limited number of substructures defined by MACCS fingerprint. Such property is expected to be helpful especially in scenarios S2 and S3 where new drug combinations were predicted. It could be speculated that more weight would be placed on the multi-omics features in the scenario of predicting drug combination responses in the cell lines outside of the training data.

5 Conclusions
In this work, we have put forward a novel approach for predicting responses of cancer drug combinations. Our method, comboLTR, is based on representing high-degree polynomial regression models through learning a factorization of the parameter tensor containing the unknown regression coefficients. We demonstrated the competitive predictive performance and time efficiency of the comboLTR method on the large NCI-ALMANAC dataset (Holbeck et al., 2017).

The results indicate that comboLTR is a practical tool for prediction and prioritization of new drug combinations for preclinical and clinical evaluation. The ability to predict full dose–response matrices enables a detailed exploration of drug response landscapes and application of different synergy models.

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Conflict of Interest: none declared.

References