A Troubling Analysis of Reproducibility and Progress in Recommender Systems Algorithms Research - Online Appendix

MAURIZIO FERRARI DACREMA, SIMONE BOGLIO, and PAOLO CREMONESI, Politecnico di Milano, Italy
DIETMAR JANNACH, University of Klagenfurt, Austria

The design of algorithms that generate personalized ranked item lists is a central topic of research in the field of recommender systems. In the past few years, in particular, approaches based on deep learning (neural) techniques have become dominant in the literature. For all of them, substantial progress over the state-of-the-art is claimed. However, indications exist of certain problems in today's research practice, e.g., with respect to the choice and optimization of the baselines used for comparison, raising questions about the published claims. In order to obtain a better understanding of the actual progress, we have tried to reproduce recent results in the area of neural recommendation approaches based on collaborative filtering. The worrying outcome of the analysis of these recent works—all were published at prestigious scientific conferences between 2015 and 2018—is that 11 out of the 12 reproducible neural approaches can be outperformed by conceptually simple methods, e.g., based on the nearest-neighbors heuristics. None of the computationally complex neural methods was actually consistently better than already existing learning-based techniques, e.g., using matrix factorization or linear models. In our analysis, we discuss common problematic issues in today's research practice, which, despite the many papers that are published on the topic, has apparently led the field to a certain level of stagnation.[1]

CCS Concepts: • **Information systems** → **Recommender systems**; *Collaborative filtering*; • **General and reference** → Evaluation.

Additional Key Words and Phrases: Recommender Systems, Deep Learning, Evaluation; Reproducibility

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[1]This paper significantly extends or own previous work presented in [12].

Authors' addresses: Maurizio Ferrari Dacrema, maurizio.ferrari@polimi.it; Simone Boglio, simone.boglio@mail.polimi.it; Paolo Cremonesi, paolo.cremonesi@polimi.it, Politecnico di Milano, Italy, Milano; Dietmar Jannach, University of Klagenfurt, Klagenfurt, Austria, dietmar.jannach@aau.at.

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Contents

A OVERVIEW

This is the additional material associated with our article [11]. This material contains the full results of our experiments of which, due to space reasons and for the sake of improving readability, only the most representative ones are reported in the paper. In Appendix B the complete list of all baselines is presented as long as a brief description and references for each of them. The following Appendices from C to N report the results of the evaluation of each deep learning algorithm, ordered by year of publication from 2015 to 2018. Lastly in Appendix O all hyperparameters for all baselines are listed with the relative search space.

The results for each deep learning algorithm we analysed are reported in a separate section. Each section is composed of three parts, a comparison of the recommendation accuracy of the algorithms, the list of all optimal hyperparameters, and a comparison of the computation time they required.

Recommendation accuracy. Compares the recommendation accuracy of all baselines and of the deep learning model in the evaluation scenario chosen by the original authors. Different tables will therefore report different metrics and cutoffs depending on the original paper. Values in bold refer to either the deep learning algorithm outperforming *all* baselines or any baseline outperforming the deep learning algorithm. In some cases the results for EASE^R and SLIM BPR may be missing, this is due to the memory requirement exceeding instance capacity as the implementations we used did not optimize memory requirements.

Optimal hyperparameters. Reports the optimal hyperparameters for all baselines and datasets. Due to the stochastic nature of the Bayesian optimization and on how many local optima the model exhibits for that dataset, multiple optimization runs may yield equivalent results but different hyperparameters.

Computation time. Compares the computation time of all algorithms on a specific Amazon AWS instance.[2] The tables and are composed by three columns. The first column (*Train time*), reports the mean and standard deviation of the time required to fit the models during the Bayesian hyperparameter optimization. In case of machine learning models requiring the selection of the number of epochs via early-stopping, the time required by the validation steps is included as it constitutes an integral part of the training procedure. The last two columns report the time required by each evaluation of the model during the Bayesian hyperparameter optimization[3] (*Recommendation Time*) and the number of recommendation lists the algorithm is able to generate per second (*Recommendation [usr/s]*). For deep learning algorithms the train and evaluation time refer to the only hyperparameter configuration we report, therefore they are not associated to any standard deviation.

It should be noted that all algorithms implemented in our repository compute a score for each item but do not directly generate the recommended items list. The sorting of such items and generation of the recommended items list is done independently from the specific recommendation model. Due to the fixed cost of ranking the items based on their score, for each user, non personalized

[2]The computation time refers to the total instance time for one AWS instance p3.2xlarge, with 8 vCPU, 30GB RAM, and one Tesla V100-SXM2-16GB GPU.

[3]Note that the evaluation time refers to an evaluation performed on the test data. During the Bayesian optimization every time a new optimal set of hyperparameters is found, using the validation data, an additional evaluation is performed on the test data. No information from the test data is ever used. For this reason, it may happen that a baseline is not associated to a standard deviation in Recommendation Time, this means that the Bayesian optimization found an optimal solution which was not improved upon and therefore only one evaluation was performed.

algorithms, i.e., TopPop, will appear to generate the same number of recommendation per second as much more complex models.

Furthermore, the implementations of the baseline algorithms vary in terms of efficiency. Some use standard solvers (PureSVD, NMF, SLIM ElasticNet), others are written in Cython[4] and compiled (KNNs, MF BPR, FunkSVD, SLIM BPR), others are written in plain Python with vectorized operations ($P^3\alpha$, $RP^3\beta$, iALS), some are single-core others take advantage of multithreading. Similarly the deep learning models are implemented in Tensorflow or Keras and with varying degrees of efficiency. Due to this heterogeneity the computational time measurements should not be taken as exact measurements but rather as a qualitative comparison.

[4]https://cython.org/

B BASELINES

Over the last 25 years, a multitude of algorithms of different types were proposed. In order to obtain a picture that is as broad as possible, we selected algorithms of different families for inclusion in our measurements. An overview of all used baselines is given in Table 1 and the relative hyperparameter ranges are reported in Appendix O.

Table 1. Overview of Baseline Methods

Family	*Method*	*Description*
Non-personalized	TopPopular	Recommends the most popular items to everyone [9]
Nearest-Neighbor	UserKNN	User-based k-nearest neighbors [23]
	ItemKNN	Item-based k-nearest neighbors [24]
Graph-based	$P^3\alpha$	A graph-based method based on random walks [8]
	$RP^3\beta$	An extension of $P^3\alpha$ [20]
Content-Based and Hybrid	ItemKNN-CBF	ItemKNN with content-based similarity [17]
	ItemKNN-CFCBF	A simple item-based hybrid CBF/CF approach [18]
	UserKNN-CBF	UserKNN with content-based similarity
	UserKNN-CFCBF	A simple user-based hybrid CBF/CF approach
Non-Neural Machine Learning	iALS	Matrix factorization for implicit feedback data [13]
	PureSVD	A basic matrix factorization method [9]
	NFM	A basic non-negative matrix factorization method [7]
	FunkSVD	Matrix factorization for rating prediction [14]
	MF BPR	Matrix factorization optimized for ranking [22]
	SLIM ElasticNet	A scalable linear model [15, 19]
	SLIM BPR	A variation of SLIM optimizing ranking [3]
	$EASE^R$	A recent linear model, similar to auto-encoders [25]

B.0.1 Popularity-Based Ranking. Recommending the most popular items to everyone is a common strategy in practice. The method **TopPopular** implements this non-personalized recommendation approach. The popularity of an item is determined by its number of implicit or explicit ratings in the given dataset.

B.0.2 Nearest-Neighbor Methods. Nearest-neighbor techniques were used in the early GroupLens system [23] and first successful reports of collaborative filtering systems also used nearest-neighbor techniques [16]. We consider both *user-based* and *item-based* variants, **UserKNN** and **ItemKNN**.

Many variants of the basic nearest-neighbor prediction scheme were proposed over the years, see [6] for an early performance comparison. In this work, we therefore consider different variations of the nearest-neighbor techniques as well. For both UserKNN and ItemKNN, the following hyperparameters can be set and were optimized in our experiments, their ranges are reported in Appendix O.

- *Neighborhood Size*: This main parameter determines how many neighbors are considered for prediction.
- *Similarity Measure*: We made experiments with the Jaccard coefficient [21] as well as Cosine [24], Asymmetric Cosine [1], Dice-Sørensen [10] and Tversky [27] similarities. Some of these similarity measures also have their own parameters, as reported in Appendix O, which we optimized as well.
- *Shrinkage*: As proposed in [4], we used a parameter (the *shrink term*) to lower the similarity between items that have only few interactions in common. The shrinkage is applied to all similarities.
- *Feature Weighting*: Using feature weighting for ratings was proposed in [28]. In our experiments, we both tested configurations with no weighting and weighting with either the TF-IDF or the BM25 scheme.
- *Normalization*: This setting determines if we should consider the denominator in the similarity measure as normalization. Only some of the similarity measures have this parameter.

B.0.3 Graph-based Methods. Traditional nearest-neighbor models consider "direct" neighborhoods by computing similarities between pairs of objects. Graph-based models can help to overcome this possible limitation relying on a broader interpretation of neighborhoods. In our study, we consider two such graph-based methods called $P^3\alpha$ [8] and $RP^3\beta$ [20]. Both methods often lead to good recommendation quality at low computational cost. Interestingly, these two methods appear to be almost unknown in the community and seldom used as baselines, despite the fact that they are very simple, effective and have been published in top-tier venues.

- ***$P^3\alpha$***: This method implements a two-steps random walk from users to items and vice-versa, where the probabilities to jump between users and items are computed from the normalized ratings raised to the power of α. The method is equivalent to a KNN item-based CF algorithm, with the similarity matrix being computed as the dot-product of the probability vectors [8]. In addition to what described in the original algorithm, we normalize each row of the similarity matrix with its $l1$ norm. The hyperparameters of the algorithm include the size of the neighborhood and the value for α.
- ***$RP^3\beta$***: This is an improved version of $P^3\alpha$ proposed in [20]. In $RP^3\beta$, each similarity between two items is computed with $P^3\alpha$ and divided by the popularity of the items raised to the power of β. Again, we normalize each row of the similarity matrix with its $l1$ norm. If β is 0, $RP^3\beta$ is equivalent to $P^3\alpha$. The hyperparameters of the algorithm are the size of the neighborhood and the values for α and β.

B.0.4 Content-based and hybrid Methods. Some of the neural methods investigated in this paper include side information about items or users. We have therefore included two simple baselines that make usage of content information.

- **ItemKNN-CBF**, **UserKNN-CBF**: A neighborhood-based content-based-filtering (CBF) approach, where we compute the item (or user) similarities based on the items' (or user's) content features (attributes) [17]. We tested the same set of similarity measures described for the collaborative KNN methods (Jaccard coefficient, Cosine, Asymmetric Cosine, Dice-Sørensen and Tversky similarity). The hyperparameters are the same as for the ItemKNN and UserKNN methods.
- **ItemKNN-CFCBF**, **UserKNN-CFCBF**: A hybrid algorithm based on item-item (or user-user) similarities and described in [18]. The similarity between items is computed by first concatenating, for each item, the vector of implicit ratings (collaborative features) and the vector of item attributes (content features) and by later computing the similarity between

the concatenated vectors. In case of user-user similarities the algorithm operates in a similar way, concatenating the vector of implicit ratings of each user with the user's content feature vector. The hyperparameters and similarity measures are the same as for ItemKNN, plus a parameter w that controls the relative importance of the content features with respect to the collaborative features. When w is 0, this algorithm is equivalent to the pure collaborative versions, either ItemKNN or UserKNN.

B.0.5 Non-Neural Machine Learning Approaches. Countless machine learning models were proposed for *top-n* recommendation tasks in the literature. In our experiments, we included a number of comparably basic models from the literature as representatives of which methods were often considered the state-of-the-art in pre-neural times.

- *Matrix Factorization (MF) Techniques*: The application of matrix decomposition methods for collaborative filtering problems was investigated already in the early years of recommender systems [5], and became a de-facto standard after the Netflix prize competition (2006-2009). We made experiments with many variants, but will limit our discussion to two main techniques which proved to consistently lead to competitive results among the different MF techniques.
  - **iALS**: In their seminal work [13], Hu et al. proposed an *Alternating Least Squares* approach for implicit feedback datasets, which turns implicit feedback signals into confidence values. The authors also proposed a particular optimization method that has the advantage of scaling well on larger datasets. A number of hyperparameters can be tuned for the method, including the number of latent factors, the confidence scaling and the regularization factor.
  - **PureSVD**: This method corresponds to a basic matrix factorization approach as proposed in [9]. To implement PureSVD, we used a standard SVD decomposition method provided in the `scikit-learn` package for Python.[5] The only hyperparameter of this method is the number of latent factors.
  - **NMF**: This method performs a *Non Negative Matrix Factorization*, which is described in [7]. As opposed to PureSVD, NFM guarantees all latent factors to be positive. We used a standard NMF decomposition method provided in the `scikit-learn` package for Python.[6] The only hyperparameter of this method is the number of latent factors.
  - **FunkSVD**: This matrix factorization algorithm was proposed by Simon Funk in his well known online article[7] during the Netflix Prize. This method optimises rating prediction via MSE. The embeddings of users and items are regularises with a Frobenius norm. In order to ensure the suitability of FunkSVD for a *top-n* recommendation task we added a hyperparameter which ensures a certain quota of the samples used during training are randomly sampled among the unseen items and are associated with a rating of 0. Another hyperparameter controls whether the model should include the global bias, user bias and item bias. Other hyperparameters include the learning rate, the regularisation coefficients, and the number of latent factors.
  - **MF BPR**: This algorithm was presented in the well known article from Rendle et al. [22] as a matrix factorization model optimizing ranking accuracy via a BPR loss. MF BPR is a widely used baseline in the article we surveyed. This method, as opposed to FunkSVD, PureSVD and NFM, has been explicitly designed for implicit interactions. Furthermore, as opposed to iALS it is trained using gradient ascent. Hyperparameters of this method include the number of latent factor, the learning rate and the regularization coefficients.

[5]https://scikit-learn.org/stable/modules/generated/sklearn.utils.extmath.randomized_svd.html
[6]https://scikit-learn.org/stable/modules/generated/sklearn.decomposition.NMF.html
[7]http://sifter.org/~simon/journal/20061211.html

- *Sparse Linear Models (SLIM)*: SLIM was proposed as a well-performing regression-based method for *top-n* recommendation tasks in [19]. In our work, we use the more scalable variant proposed in [15] (**SLIM ElasticNet**) which learns the item similarity matrix one item at a time (e.g. one column w at a time) by solving a regression problem in such a way that the interactions for the target item y are learned by using all other interactions as training data. To implement *SLIM ElasticNet* we used a standard ElasticNet solver provided in the `scikit-learn` package for Python.[8] The hyperparameters of this method include the ratio of *l1* and *l2* regularizations as well as a regularization magnitude coefficient.
- *Sparse Linear Models BPR*: This algorithm is a variant of the previously mentioned SLIM ElacticNet which optimizes ranking accuracy rather than prediction error (**SLIM BPR**) [2, 3, 26]. The algorithm learns an item-item similarity matrix by optimizing the BPR loss function, described in [22], via gradient ascent. The hyperparameters of this method include the number of neighbours as described in the Nearest-Neighbor Methods, the regularization coefficients and whether the learned similarity matrix should be symmetric or not.
- ***EASE***^{R}: In a recent article [25] the author showed that an "embarrassingly shallow" linear model, which shares similarities with an auto-encoder, can produce highly-accurate recommendations that often outperform existing and much more complex techniques. A peculiarity of this model is the existence of a closed-form solution for the training objective which results in very fast training. The only hyperparameter is the choice of the regularization factor.
  This algorithm has been published in 2019 and, as such, the papers covered by our study could not include EASE^R as a baseline. However, we include EASE^R to investigate whether shallow auto-encoders are able to provide, on average, more accurate recommendations with respect to complex deep-learning architectures.

[8] https://scikit-learn.org/stable/modules/generated/sklearn.linear_model.ElasticNet.html

C KDD: COLLABORATIVE DEEP LEARNING

This algorithm is evaluated in the same experimental conditions and on the same data as *CVAE*. For the full results please refer to Section E.

D SIGIR: COLLABORATIVE MEMORY NETWORKS

Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 2 and 3. The results of our evaluation can be seen in Table 4 (CiteULike), Table 5 (Epinions) and Table 6 (Pinterest). The corresponding optimal hyperparameters are reported in Table 7 (collaborative KNNs), Table 8 (non-neural machine learning and graph based) and Table 9 (CMN). In Table 4 and 5 we report only the best performing CMN, which corresponds to CMN-3, hence with three hops.

Lastly, the time required to train and evaluate the models is reported in Table 10 (CiteULike), Table 11 (Epinions) and Table 12 (Pinterest).

Table 2. Dataset characteristics.

Dataset	Interactions	Items	Users	Sparsity
Epinions	664.8 k	139.7 k	40.1 k	99.98%
CiteULike-a	204.9 k	16.9 k	5.5 k	99.78%
Pinterest	1.5 M	9.9 k	55.1 k	99.73%

Table 3. Dataset popularity bias characteristics.

	Max pop	Min pop	Avg pop	Gini Index	Shannon	Herfindahl
Citeulike	321.00	1.00	12.07	0.37	13.65	1.00
Pinterest	1636.00	1.00	147.60	0.45	12.77	1.00
Epinions	2026.00	1.00	4.76	0.69	15.11	1.00

Table 4. Experimental results on the metrics and cutoffs reported in the original paper.

	Citeulike			
	HR@5	NDCG@5	HR@10	NDCG@10
Random	0.0486	0.0288	0.0919	0.0426
TopPop	0.1810	0.1226	0.2774	0.1537
UserKNN CF cosine	**0.8231**	**0.7027**	**0.8962**	**0.7265**
UserKNN CF dice	**0.8099**	**0.6839**	**0.8836**	**0.7079**
UserKNN CF jaccard	**0.8116**	**0.6880**	**0.8838**	**0.7115**
UserKNN CF asymmetric	**0.8226**	**0.7039**	**0.8959**	**0.7279**
UserKNN CF tversky	**0.8121**	**0.6892**	**0.8867**	**0.7135**
ItemKNN CF cosine	**0.8247**	**0.7045**	**0.8925**	**0.7267**
ItemKNN CF dice	**0.8089**	**0.6823**	**0.8863**	**0.7075**
ItemKNN CF jaccard	**0.8065**	**0.6793**	**0.8861**	**0.7053**
ItemKNN CF asymmetric	**0.8233**	**0.7041**	**0.8944**	**0.7274**
ItemKNN CF tversky	**0.8081**	**0.6796**	**0.8874**	**0.7055**
P3alpha	**0.8272**	**0.7144**	**0.8971**	**0.7370**
RP3beta	**0.8326**	**0.7227**	**0.9002**	**0.7447**
EASE R	**0.8107**	**0.6966**	**0.8771**	**0.7182**
SLIM BPR	**0.8099**	**0.6916**	**0.8861**	**0.7164**
SLIMElasticNet	**0.8265**	**0.7168**	**0.8908**	**0.7376**
MF BPR	0.7316	0.6053	0.8245	0.6356
MF FunkSVD	0.7860	0.6488	0.8672	0.6752
PureSVD	0.7233	0.6020	0.7954	0.6254
NMF	0.7161	0.5534	0.8245	0.5887
IALS	**0.8308**	**0.7085**	**0.9006**	**0.7313**
CMN	0.7874	0.6505	0.8746	0.6790

Table 5. Experimental results on the metrics and cutoffs reported in the original paper.

	Epinions			
	HR@5	NDCG@5	HR@10	NDCG@10
Random	0.0489	0.0290	0.0988	0.0449
TopPop	**0.5492**	**0.4204**	**0.6672**	**0.4587**
UserKNN CF cosine	0.4282	0.3631	0.4764	0.3787
UserKNN CF dice	0.4108	0.3475	0.4589	0.3630
UserKNN CF jaccard	0.4108	0.3473	0.4589	0.3628
UserKNN CF asymmetric	0.4294	0.3642	0.4767	0.3795
UserKNN CF tversky	0.4207	0.3571	0.4700	0.3731
ItemKNN CF cosine	0.4309	0.3584	0.4854	0.3760
ItemKNN CF dice	0.4088	0.3426	0.4631	0.3601
ItemKNN CF jaccard	0.4088	0.3427	0.4631	0.3602
ItemKNN CF asymmetric	0.4149	0.3437	0.4761	0.3635
ItemKNN CF tversky	0.4179	0.3476	0.4757	0.3662
P3alpha	0.4008	0.3411	0.4389	0.3533
RP3beta	0.3928	0.3329	0.4341	0.3462
EASE R	-	-	-	-
SLIM BPR	0.3988	0.3393	0.4422	0.3533
SLIMElasticNet	0.4133	0.3471	0.4667	0.3643
MF BPR	0.4668	0.3662	**0.5594**	0.3962
MF FunkSVD	**0.5427**	**0.4196**	**0.6567**	**0.4566**
PureSVD	0.4073	0.3069	0.5045	0.3384
NMF	0.4055	0.3218	0.4951	0.3508
IALS	0.0519	0.0316	0.1003	0.0470
CMN	0.4699	0.3781	0.5399	0.4008

Table 6. Experimental results on the metrics and cutoffs reported in the original paper.

	Pinterest			
	HR@5	NDCG@5	HR@10	NDCG@10
Random	0.0509	0.0296	0.1003	0.0454
TopPop	0.1665	0.1064	0.2740	0.1409
UserKNN CF cosine	**0.7017**	**0.5050**	0.8614	**0.5570**
UserKNN CF dice	**0.7026**	**0.5053**	0.8634	**0.5578**
UserKNN CF jaccard	**0.7034**	**0.5062**	0.8639	**0.5585**
UserKNN CF asymmetric	0.7005	**0.5037**	0.8630	**0.5567**
UserKNN CF tversky	**0.7024**	**0.5047**	0.8636	**0.5572**
ItemKNN CF cosine	**0.7132**	**0.5116**	**0.8781**	**0.5653**
ItemKNN CF dice	**0.7095**	**0.5091**	**0.8766**	**0.5635**
ItemKNN CF jaccard	**0.7094**	**0.5086**	**0.8764**	**0.5630**
ItemKNN CF asymmetric	**0.7126**	**0.5110**	**0.8776**	**0.5648**
ItemKNN CF tversky	**0.7095**	**0.5086**	**0.8761**	**0.5629**
P3alpha	0.6990	**0.5034**	0.8596	**0.5559**
RP3beta	**0.7147**	**0.5150**	**0.8772**	**0.5680**
EASE R	**0.7050**	**0.5106**	0.8559	**0.5599**
SLIM BPR	**0.7120**	**0.5151**	**0.8733**	**0.5678**
SLIMElasticNet	**0.7084**	**0.5107**	**0.8683**	**0.5628**
MF BPR	0.6924	0.4886	**0.8694**	0.5463
MF FunkSVD	**0.7088**	**0.5037**	**0.8686**	**0.5559**
PureSVD	0.6619	0.4721	0.8146	0.5219
NMF	0.6550	0.4618	0.8287	0.5183
IALS	**0.7219**	**0.5175**	**0.8677**	**0.5652**
CMN	0.7013	0.5005	0.8674	0.5547

Table 7. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Citeulike	Pinterest	Epinions
UserKNN CF cosine	topK	578	668	1000
	shrink	0	0	0
	similarity	cosine	cosine	cosine
	normalize	True	True	True
	feature weighting	BM25	none	TF-IDF
UserKNN CF dice	topK	627	818	1000
	shrink	0	0	0
	similarity	dice	dice	dice
	normalize	False	True	False
UserKNN CF jaccard	topK	637	807	1000
	shrink	0	0	0
	similarity	jaccard	jaccard	jaccard
	normalize	False	True	False
UserKNN CF asymmetric	topK	690	1000	1000
	shrink	1000	0	163
	similarity	asymmetric	asymmetric	asymmetric
	normalize	True	True	True
	asymmetric alpha	1.0291	0.4622	0.4379
	feature weighting	BM25	BM25	TF-IDF
UserKNN CF tversky	topK	533	940	935
	shrink	35	0	9
	similarity	tversky	tversky	tversky
	normalize	True	True	True
	tversky alpha	1.4634	2.0000	0.1591
	tversky beta	0.0885	0.0000	1.9682
ItemKNN CF cosine	topK	594	942	1000
	shrink	999	1000	448
	similarity	cosine	cosine	cosine
	normalize	True	True	False
	feature weighting	TF-IDF	BM25	TF-IDF
ItemKNN CF dice	topK	996	981	1000
	shrink	11	0	1000
	similarity	dice	dice	dice
	normalize	False	False	True
ItemKNN CF jaccard	topK	480	983	1000
	shrink	3	0	1000
	similarity	jaccard	jaccard	jaccard
	normalize	True	True	False
ItemKNN CF asymmetric	topK	1000	1000	1000
	shrink	649	845	850
	similarity	asymmetric	asymmetric	asymmetric
	normalize	True	True	True
	asymmetric alpha	0.2742	0.2281	1.5411
	feature weighting	TF-IDF	BM25	none
ItemKNN CF tversky	topK	421	1000	1000
	shrink	28	0	555
	similarity	tversky	tversky	tversky
	normalize	True	True	True
	tversky alpha	0.0103	1.9767	0.0000
	tversky beta	0.9612	2.0000	0.0000

Table 8. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Citeulike	Pinterest	Epinions
$P^3\alpha$	topK	653	453	1000
	alpha	0.6310	1.1895	0.1164
	normalize similarity	False	True	False
$RP^3\beta$	topK	764	816	1000
	alpha	0.7110	1.1916	0.0000
	beta	0.2297	0.4365	0.0000
	normalize similarity	True	True	False
$EASE^R$	l2 norm	4.60E+02	1.72E+03	-
SLIM BPR	topK	803	726	1000
	epochs	165	235	370
	symmetric	False	True	False
	sgd mode	adam	adagrad	adagrad
	lambda i	1.00E-02	1.00E-05	1.00E-02
	lambda j	1.00E-02	3.06E-05	1.00E-02
	learning rate	1.00E-04	1.00E-01	1.00E-04
SLIMElasticNet	topK	1000	705	1000
	l1 ratio	4.21E-05	1.55E-04	1.00E-05
	alpha	0.0265	0.0316	0.2911
MF BPR	sgd mode	adam	adagrad	adagrad
	epochs	1045	935	995
	num factors	175	146	200
	batch size	512	128	16
	positive reg	9.89E-03	7.72E-03	1.00E-02
	negative reg	7.25E-03	1.00E-02	1.00E-02
	learning rate	2.80E-03	4.63E-02	1.00E-01
MF FunkSVD	sgd mode	adam	adam	adam
	epochs	300	500	75
	use bias	True	False	True
	batch size	16	8	4
	num factors	55	37	1
	item reg	4.02E-05	1.00E-05	1.00E-05
	user reg	1.00E-02	1.00E-02	9.01E-03
	learning rate	2.44E-03	5.99E-04	1.58E-04
	negative quota	0.2792	0.0941	0.4998
PureSVD	num factors	320	77	1
NMF	num factors	122	77	45
	solver	mult. update	coord. descent	coord. descent
	init type	nndsvda	nndsvda	random
	beta loss	kullback-leibler	frobenius	frobenius
iALS	num factors	115	52	49
	confidence scaling	linear	linear	log
	alpha	15.4014	50.0000	9.8676
	epsilon	0.4163	0.0052	0.0013
	reg	1.00E-05	1.00E-05	6.20E-03
	epochs	60	90	100

Table 9. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Citeulike	Pinterest	Epinions
CMN	epochs	50	5	45
	epochs gmf	100	100	100
	hops	3	3	3
	neg samples	4	4	4
	reg l2 cmn	1.00E-01	1.00E-01	1.00E-01
	reg l2 gmf	1.00E-04	1.00E-04	1.00E-04
	pretrain	True	True	True
	learning rate	1.00E-03	1.00E-03	1.00E-03
	verbose	False	False	False
	batch size	128	256	128
	embed size	50	50	40

Table 10. Comparison of the computation time for the different algorithms.

	Citeulike		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	4.83 [sec]	1150
TopPop	0.01 [sec]	5.46 [sec]	1017
UserKNN CF cosine	0.52 ± 0.04 [sec]	9.76 ± 0.23 [sec]	566
UserKNN CF dice	0.52 ± 0.04 [sec]	9.41 ± 0.39 [sec]	575
UserKNN CF jaccard	0.52 ± 0.04 [sec]	9.69 ± 0.38 [sec]	572
UserKNN CF asymmetric	0.51 ± 0.04 [sec]	9.80 ± 0.07 [sec]	574
UserKNN CF tversky	0.50 ± 0.04 [sec]	9.58 ± 0.02 [sec]	580
ItemKNN CF cosine	3.10 ± 0.31 [sec]	9.75 ± 0.41 [sec]	564
ItemKNN CF dice	3.06 ± 0.21 [sec]	9.70 ± 0.38 [sec]	554
ItemKNN CF jaccard	3.06 ± 0.21 [sec]	9.87 ± 0.16 [sec]	575
ItemKNN CF asymmetric	3.24 ± 0.21 [sec]	9.73 ± 0.44 [sec]	553
ItemKNN CF tversky	3.02 ± 0.24 [sec]	9.70 ± 0.17 [sec]	581
$P^3\alpha$	13.78 ± 2.87 [sec]	9.56 ± 0.13 [sec]	583
$RP^3\beta$	15.82 ± 3.05 [sec]	9.51 ± 0.26 [sec]	576
$EASE^R$	102.76 [sec] / 1.71 ± 0.01 [min]	8.99 ± 0.05 [sec]	612
SLIM BPR	645.01 [sec] / 10.75 ± 4.22 [min]	10.16 ± 0.22 [sec]	538
SLIMElasticNet	236.77 [sec] / 3.95 ± 1.56 [min]	9.79 ± 0.66 [sec]	559
MF BPR	776.37 [sec] / 12.94 ± 8.09 [min]	6.51 ± 1.04 [sec]	879
MF FunkSVD	1057.07 [sec] / 17.62 ± 12.82 [min]	6.12 ± 0.37 [sec]	881
PureSVD	1.23 ± 0.47 [sec]	7.32 ± 0.21 [sec]	744
NMF	153.39 [sec] / 2.56 ± 2.07 [min]	6.71 ± 0.50 [sec]	870
iALS	593.57 [sec] / 9.89 ± 4.71 [min]	5.92 ± 0.21 [sec]	911
CMN	6818.32 [sec] / 1.89 [hour]	20.18 [sec]	275

Table 11. Comparison of the computation time for the different algorithms.

	Epinions		
	Train time	Recommendation Time	[usr/s]
Random	0.01 [sec]	56.42 [sec]	712
TopPop	0.02 [sec]	91.41 [sec] / 1.52 [min]	439
UserKNN CF cosine	12.81 ± 0.45 [sec]	120.93 [sec] / 2.02 ± 0.02 [min]	330
UserKNN CF dice	12.51 ± 0.39 [sec]	119.91 [sec] / 2.00 ± 0.03 [min]	329
UserKNN CF jaccard	12.51 ± 0.41 [sec]	120.24 [sec] / 2.00 ± 0.02 [min]	331
UserKNN CF asymmetric	13.04 ± 0.37 [sec]	121.49 [sec] / 2.02 ± 0.03 [min]	325
UserKNN CF tversky	12.66 ± 0.36 [sec]	121.45 [sec] / 2.02 ± 0.01 [min]	331
ItemKNN CF cosine	125.68 [sec] / 2.09 ± 0.14 [min]	128.99 [sec] / 2.15 ± 0.05 [min]	305
ItemKNN CF dice	122.99 [sec] / 2.05 ± 0.01 [min]	127.09 [sec] / 2.12 ± 0.04 [min]	311
ItemKNN CF jaccard	123.08 [sec] / 2.05 ± 0.01 [min]	128.41 [sec] / 2.14 ± 0.03 [min]	306
ItemKNN CF asymmetric	126.35 [sec] / 2.11 ± 0.02 [min]	129.97 [sec] / 2.17 ± 0.07 [min]	303
ItemKNN CF tversky	125.31 [sec] / 2.09 ± 0.01 [min]	127.61 [sec] / 2.13 ± 0.06 [min]	306
$P^3\alpha$	367.87 [sec] / 6.13 ± 0.19 [min]	116.08 [sec] / 1.93 ± 0.03 [min]	341
$RP^3\beta$	395.01 [sec] / 6.58 ± 0.20 [min]	116.68 [sec] / 1.94 ± 0.03 [min]	339
$EASE^R$	-	-	-
SLIM BPR	42149.10 [sec] / 11.71 ± 5.47 [hour]	124.94 [sec] / 2.08 ± 0.07 [min]	323
SLIMElasticNet	14201.25 [sec] / 3.94 ± 1.31 [hour]	127.63 [sec] / 2.13 ± 0.14 [min]	310
MF BPR	10857.32 [sec] / 3.02 ± 1.65 [hour]	98.43 [sec] / 1.64 ± 0.28 [min]	440
MF FunkSVD	3409.08 [sec] / 56.82 ± 68.92 [min]	105.37 [sec] / 1.76 ± 0.19 [min]	327
PureSVD	2.36 ± 3.67 [sec]	88.22 [sec] / 1.47 ± 0.04 [min]	464
NMF	1754.00 [sec] / 29.23 ± 18.12 [min]	100.15 [sec] / 1.67 ± 0.18 [min]	448
iALS	4470.54 [sec] / 1.24 ± 0.79 [hour]	87.28 [sec] / 1.45 ± 0.00 [min]	459
CMN	33203.75 [sec] / 9.22 [hour]	292.74 [sec] / 4.88 [min]	137

Table 12. Comparison of the computation time for the different algorithms.

	Pinterest		
	Train time	Recommendation Time	[usr/s]
Random	0.02 [sec]	47.56 [sec]	1160
TopPop	0.04 [sec]	52.75 [sec]	1046
UserKNN CF cosine	28.98 ± 1.55 [sec]	94.03 [sec] / 1.57 ± 0.03 [min]	586
UserKNN CF dice	29.42 ± 0.98 [sec]	94.33 [sec] / 1.57 ± 0.02 [min]	578
UserKNN CF jaccard	29.45 ± 1.21 [sec]	94.86 [sec] / 1.58 ± 0.01 [min]	582
UserKNN CF asymmetric	30.05 ± 1.40 [sec]	94.93 [sec] / 1.58 ± 0.06 [min]	567
UserKNN CF tversky	28.91 ± 1.58 [sec]	95.05 [sec] / 1.58 ± 0.02 [min]	571
ItemKNN CF cosine	1.82 ± 0.19 [sec]	92.88 [sec] / 1.55 ± 0.02 [min]	592
ItemKNN CF dice	1.76 ± 0.21 [sec]	91.06 [sec] / 1.52 ± 0.04 [min]	594
ItemKNN CF jaccard	1.77 ± 0.17 [sec]	91.28 [sec] / 1.52 ± 0.04 [min]	597
ItemKNN CF asymmetric	1.78 ± 0.17 [sec]	90.51 [sec] / 1.51 ± 0.05 [min]	593
ItemKNN CF tversky	1.74 ± 0.16 [sec]	90.53 [sec] / 1.51 ± 0.04 [min]	595
$P^3\alpha$	8.71 ± 2.25 [sec]	88.71 [sec] / 1.48 ± 0.02 [min]	627
$RP^3\beta$	9.23 ± 2.85 [sec]	90.04 [sec] / 1.50 ± 0.03 [min]	608
$EASE^R$	22.30 ± 0.27 [sec]	76.12 [sec] / 1.27 ± 0.02 [min]	721
SLIM BPR	3594.20 [sec] / 59.90 ± 28.93 [min]	91.58 [sec] / 1.53 ± 0.03 [min]	597
SLIMElasticNet	433.57 [sec] / 7.23 ± 2.50 [min]	91.23 [sec] / 1.52 ± 0.04 [min]	595
MF BPR	6439.39 [sec] / 1.79 ± 1.12 [hour]	64.56 [sec] / 1.08 ± 0.18 [min]	755
MF FunkSVD	8220.55 [sec] / 2.28 ± 1.76 [hour]	58.83 ± 10.08 [sec]	1006
PureSVD	2.33 ± 1.89 [sec]	56.22 ± 0.27 [sec]	984
NMF	686.16 [sec] / 11.44 ± 9.74 [min]	72.56 [sec] / 1.21 ± 0.26 [min]	937
iALS	2694.24 [sec] / 44.90 ± 36.27 [min]	57.41 ± 1.73 [sec]	955
CMN	28100.23 [sec] / 7.81 [hour]	354.04 [sec] / 5.90 [min]	156

E KDD: COLLABORATIVE VARIATIONAL AUTOENCODERS

Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 13 and 14. The results of our evaluation can be seen in Table 15 (citeULike-a, P=1), Table 16 (citeULike-a, P=10), Table 17 (citeULike-t, P=1), Table 18 (citeULike-t, P=10). The corresponding optimal hyperparameters are reported in Table 19 (collaborative KNNs), Table 20 (non-neural machine learning and graph based), Table 21 (content-based KNNs), Table 22 (hybrid KNNs) and Table 23 (CVAE and CDL).

Lastly, the time required to train and evaluate the models is reported in Table 24 (citeULike-a, P=1), Table 25 (citeULike-a, P=10), Table 26 (citeULike-t, P=1), Table 27 (citeULike-t, P=10).

Table 13. Dataset characteristics.

Dataset	Interactions	Items	Users	Sparsity	Item features
CiteULike-a	204.9 k	16.9 k	5.5 k	99.78%	8.0 k
CiteULike-t	134.8 k	25.9 k	7.9 k	99.93%	20.0 k
NetflixPrize	15.3 M	9.2 k	407.2 k	99.59%	20.0 k

Table 14. Train data density for the different experimental settings of CDL.

Dataset	Experiment	Interactions	Density
CiteULike-a	P = 1	5.5 k	$5.8e-5$
CiteULike-a	P = 10	55.5 k	$5.8e-4$
CiteULike-t	P = 1	7.9 k	$3.8e-5$
CiteULike-t	P = 10	53.3 k	$2.5e-4$

Table 15. Experimental results on the metrics and cutoffs reported in the original paper.

	CiteULike-a P=1					
	REC@50	REC@100	REC@150	REC@200	REC@250	REC@300
Random	0.0033	0.0065	0.0096	0.0126	0.0155	0.0185
TopPop	0.0253	0.0389	0.0486	0.0589	0.0651	0.0704
UserKNN CF cosine	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
UserKNN CF dice	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
UserKNN CF jaccard	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
UserKNN CF asymmetric	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
UserKNN CF tversky	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
ItemKNN CF cosine	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
ItemKNN CF dice	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
ItemKNN CF jaccard	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
ItemKNN CF asymmetric	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
ItemKNN CF tversky	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
P3alpha	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
RP3beta	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
EASE R	0.0043	0.0073	0.0120	0.0160	0.0203	0.0235
SLIM BPR	0.0027	0.0052	0.0071	0.0102	0.0130	0.0155
SLIMElasticNet	0.0026	0.0053	0.0069	0.0102	0.0127	0.0154
MF BPR	0.0046	0.0082	0.0119	0.0154	0.0188	0.0223
MF FunkSVD	0.0047	0.0087	0.0125	0.0161	0.0194	0.0227
PureSVD	0.0055	0.0111	0.0168	0.0226	0.0289	0.0356
NMF	0.0036	0.0067	0.0090	0.0121	0.0142	0.0167
IALS	0.0050	0.0102	0.0149	0.0190	0.0235	0.0279
ItemKNN CBF cosine	0.0242	0.0267	0.0284	0.0317	0.0341	0.0367
ItemKNN CBF dice	0.0210	0.0235	0.0253	0.0287	0.0310	0.0336
ItemKNN CBF jaccard	0.0253	0.0282	0.0301	0.0335	0.0360	0.0386
ItemKNN CBF asymmetric	0.0256	0.0295	0.0316	0.0350	0.0379	0.0405
ItemKNN CBF tversky	0.0173	0.0200	0.0217	0.0251	0.0275	0.0300
ItemKNN CFCBF cosine	0.0034	0.0061	0.0076	0.0110	0.0135	0.0161
ItemKNN CFCBF dice	0.0236	0.0262	0.0279	0.0313	0.0336	0.0362
ItemKNN CFCBF jaccard	0.0553	0.0614	0.0639	0.0670	0.0691	0.0717
ItemKNN CFCBF asymmetric	0.0029	0.0055	0.0071	0.0104	0.0130	0.0156
ItemKNN CFCBF tversky	0.0448	0.0512	0.0547	0.0583	0.0612	0.0639
CVAE	0.0768	0.1171	**0.1485**	**0.1744**	**0.1973**	**0.2168**
CDL	**0.0855**	**0.1208**	0.1445	0.1623	0.1767	0.1901

Table 16. Experimental results on the metrics and cutoffs reported in the original paper.

	CiteULike-a P=10					
	REC@50	REC@100	REC@150	REC@200	REC@250	REC@300
Random	0.0034	0.0062	0.0090	0.0120	0.0146	0.0174
TopPop	0.0040	0.0078	0.0103	0.0204	0.0230	0.0258
UserKNN CF cosine	0.0769	0.1174	0.1443	0.1670	0.1859	0.2010
UserKNN CF dice	0.0788	0.1186	0.1463	0.1689	0.1875	0.2030
UserKNN CF jaccard	**0.0806**	0.1207	0.1480	0.1705	0.1887	0.2034
UserKNN CF asymmetric	0.0769	0.1173	0.1441	0.1671	0.1859	0.2013
UserKNN CF tversky	0.0799	0.1192	0.1466	0.1696	0.1880	0.2025
ItemKNN CF cosine	**0.0989**	0.1441	0.1752	0.1982	0.2156	0.2300
ItemKNN CF dice	**0.0945**	0.1373	0.1675	0.1912	0.2092	0.2233
ItemKNN CF jaccard	**0.0917**	0.1340	0.1642	0.1876	0.2062	0.2207
ItemKNN CF asymmetric	**0.0890**	0.1334	0.1631	0.1865	0.2065	0.2215
ItemKNN CF tversky	**0.0990**	0.1428	0.1736	0.1972	0.2143	0.2281
P3alpha	**0.0907**	0.1341	0.1636	0.1865	0.2055	0.2206
RP3beta	**0.0963**	0.1408	0.1692	0.1908	0.2090	0.2239
EASE R	**0.0835**	0.1242	0.1528	0.1771	0.1956	0.2100
SLIM BPR	**0.0876**	0.1308	0.1583	0.1821	0.2005	0.2165
SLIMElasticNet	**0.0869**	0.1281	0.1561	0.1789	0.1970	0.2115
MF BPR	0.0680	0.1011	0.1225	0.1402	0.1542	0.1663
MF FunkSVD	0.0483	0.0866	0.1157	0.1412	0.1636	0.1816
PureSVD	0.0715	0.1079	0.1313	0.1491	0.1636	0.1759
NMF	0.0628	0.1013	0.1285	0.1505	0.1679	0.1843
IALS	0.0779	0.1388	0.1834	0.2186	0.2472	0.2706
ItemKNN CBF cosine	**0.2235**	**0.3180**	**0.3829**	**0.4283**	**0.4651**	**0.4950**
ItemKNN CBF dice	**0.1734**	**0.2495**	**0.3035**	**0.3455**	**0.3798**	**0.4076**
ItemKNN CBF jaccard	**0.1752**	**0.2522**	**0.3045**	**0.3457**	**0.3794**	**0.4062**
ItemKNN CBF asymmetric	**0.2234**	**0.3186**	**0.3835**	**0.4288**	**0.4641**	**0.4945**
ItemKNN CBF tversky	**0.1748**	**0.2507**	**0.3040**	**0.3466**	**0.3814**	**0.4097**
ItemKNN CFCBF cosine	**0.1858**	**0.2816**	**0.3445**	**0.3930**	**0.4335**	**0.4642**
ItemKNN CFCBF dice	**0.1803**	**0.2600**	**0.3126**	**0.3558**	**0.3876**	**0.4126**
ItemKNN CFCBF jaccard	**0.1855**	**0.2650**	**0.3175**	**0.3598**	**0.3924**	**0.4181**
ItemKNN CFCBF asymmetric	**0.1712**	**0.2690**	**0.3355**	**0.3845**	**0.4237**	**0.4565**
ItemKNN CFCBF tversky	**0.1832**	**0.2618**	**0.3159**	**0.3577**	**0.3899**	**0.4162**
CVAE	0.0805	0.1569	0.2232	0.2760	0.3250	0.3687
CDL	0.0580	0.1108	0.1546	0.1946	0.2314	0.2640

Table 17. Experimental results on the metrics and cutoffs reported in the original paper.

	CiteULike-t P=1					
	REC@50	REC@100	REC@150	REC@200	REC@250	REC@300
Random	0.0018	0.0037	0.0057	0.0074	0.0093	0.0109
TopPop	0.0134	0.0179	0.0247	0.0395	0.0456	0.0511
UserKNN CF cosine	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
UserKNN CF dice	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
UserKNN CF jaccard	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
UserKNN CF asymmetric	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
UserKNN CF tversky	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
ItemKNN CF cosine	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
ItemKNN CF dice	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
ItemKNN CF jaccard	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
ItemKNN CF asymmetric	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
ItemKNN CF tversky	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
P3alpha	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
RP3beta	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
EASE R	0.0034	0.0064	0.0096	0.0139	0.0160	0.0192
SLIM BPR	0.0013	0.0038	0.0066	0.0084	0.0102	0.0122
SLIMElasticNet	0.0012	0.0038	0.0065	0.0084	0.0104	0.0123
MF BPR	0.0054	0.0094	0.0125	0.0153	0.0176	0.0203
MF FunkSVD	0.0029	0.0057	0.0083	0.0107	0.0130	0.0151
PureSVD	0.0053	0.0094	0.0140	0.0193	0.0246	0.0283
NMF	0.0037	0.0054	0.0074	0.0089	0.0107	0.0129
IALS	0.0061	0.0100	0.0137	0.0173	0.0206	0.0245
ItemKNN CBF cosine	**0.0858**	**0.1248**	**0.1549**	**0.1790**	**0.2000**	**0.2180**
ItemKNN CBF dice	**0.1133**	**0.1566**	**0.1887**	**0.2122**	**0.2312**	**0.2478**
ItemKNN CBF jaccard	**0.1136**	**0.1567**	**0.1874**	**0.2116**	**0.2283**	**0.2433**
ItemKNN CBF asymmetric	**0.0916**	**0.1274**	**0.1493**	**0.1633**	**0.1743**	**0.1813**
ItemKNN CBF tversky	**0.1135**	**0.1566**	**0.1881**	**0.2125**	**0.2315**	**0.2490**
ItemKNN CFCBF cosine	**0.0944**	**0.1349**	**0.1647**	**0.1864**	**0.2059**	**0.2243**
ItemKNN CFCBF dice	**0.1129**	**0.1552**	**0.1867**	**0.2105**	**0.2300**	**0.2463**
ItemKNN CFCBF jaccard	**0.1133**	**0.1559**	**0.1848**	**0.2066**	**0.2218**	**0.2338**
ItemKNN CFCBF asymmetric	**0.0448**	0.0525	0.0554	0.0575	0.0590	0.0609
ItemKNN CFCBF tversky	**0.1133**	**0.1555**	**0.1855**	**0.2085**	**0.2249**	**0.2389**
CVAE	0.0430	0.0639	0.0803	0.0950	0.1076	0.1200
CDL	0.0351	0.0573	0.0715	0.0822	0.0915	0.0989

Table 18. Experimental results on the metrics and cutoffs reported in the original paper.

	CiteULike-t P=10					
	REC@50	REC@100	REC@150	REC@200	REC@250	REC@300
Random	0.0019	0.0039	0.0055	0.0079	0.0106	0.0124
TopPop	0.0578	0.0862	0.1100	0.1257	0.1416	0.1568
UserKNN CF cosine	0.2141	0.2661	0.2964	0.3169	0.3320	0.3437
UserKNN CF dice	0.2138	0.2661	0.2958	0.3171	0.3325	0.3444
UserKNN CF jaccard	0.2139	0.2648	0.2954	0.3154	0.3308	0.3426
UserKNN CF asymmetric	0.2134	0.2656	0.2963	0.3170	0.3341	0.3458
UserKNN CF tversky	0.2120	0.2651	0.2955	0.3172	0.3336	0.3462
ItemKNN CF cosine	0.2133	0.2658	0.2964	0.3173	0.3342	0.3457
ItemKNN CF dice	0.2157	0.2681	0.2995	0.3206	0.3366	0.3492
ItemKNN CF jaccard	0.2167	0.2685	0.2994	0.3205	0.3366	0.3491
ItemKNN CF asymmetric	0.2027	0.2616	0.2958	0.3197	0.3381	0.3525
ItemKNN CF tversky	0.2015	0.2606	0.2949	0.3190	0.3372	0.3521
P3alpha	0.2276	0.2769	0.3069	0.3280	0.3450	0.3571
RP3beta	0.2073	0.2636	0.2975	0.3210	0.3398	0.3538
EASE R	0.2056	0.2532	0.2821	0.3025	0.3171	0.3307
SLIM BPR	0.2187	0.2681	0.2988	0.3196	0.3383	0.3516
SLIMElasticNet	0.2102	0.2612	0.2930	0.3129	0.3315	0.3446
MF BPR	0.1551	0.1990	0.2279	0.2482	0.2649	0.2824
MF FunkSVD	0.1231	0.1613	0.1857	0.2019	0.2155	0.2276
PureSVD	0.1329	0.1730	0.1994	0.2215	0.2393	0.2547
NMF	0.1082	0.1429	0.1771	0.2002	0.2199	0.2420
IALS	0.2338	0.3107	0.3566	0.3925	0.4175	0.4374
ItemKNN CBF cosine	0.1625	0.2237	0.2682	0.3001	0.3269	0.3493
ItemKNN CBF dice	0.1665	0.2323	0.2832	0.3206	0.3512	0.3756
ItemKNN CBF jaccard	0.1681	0.2342	0.2851	0.3210	0.3505	0.3761
ItemKNN CBF asymmetric	0.1630	0.2259	0.2689	0.3031	0.3314	0.3562
ItemKNN CBF tversky	0.1599	0.2291	0.2791	0.3170	0.3469	0.3727
ItemKNN CFCBF cosine	**0.2675**	**0.3490**	**0.3939**	0.4246	0.4519	0.4740
ItemKNN CFCBF dice	0.2166	0.2868	0.3361	0.3738	0.4024	0.4284
ItemKNN CFCBF jaccard	0.2172	0.2880	0.3363	0.3741	0.4026	0.4271
ItemKNN CFCBF asymmetric	**0.2412**	0.3160	0.3663	0.4051	0.4321	0.4548
ItemKNN CFCBF tversky	0.2178	0.2872	0.3383	0.3758	0.4053	0.4279
CVAE	0.2387	0.3274	0.3849	**0.4263**	**0.4606**	**0.4854**
CDL	0.2231	0.3019	0.3565	0.4031	0.4351	0.4618

Table 19. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	CiteULike-a P=1	CiteULike-a P=10	CiteULike-t P=1	CiteULike-t P=10
UserKNN CF cosine	topK	844	455	945	347
	shrink	998	490	229	1000
	similarity	cosine	cosine	cosine	cosine
	normalize	False	False	False	True
	feature weighting	BM25	TF-IDF	TF-IDF	none
UserKNN CF dice	topK	396	317	203	359
	shrink	551	1000	832	1000
	similarity	dice	dice	dice	dice
	normalize	False	True	False	False
UserKNN CF jaccard	topK	436	348	660	327
	shrink	918	1000	205	1000
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	False	False	True	True
UserKNN CF asymmetric	topK	748	483	584	777
	shrink	733	1000	709	314
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	1.9382	2.0000	1.5064	1.9573
	feature weighting	none	none	BM25	none
UserKNN CF tversky	topK	808	870	264	892
	shrink	917	967	705	981
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	1.3044	0.0119	0.2812	0.1122
	tversky beta	1.5023	1.9836	1.1578	0.0128
ItemKNN CF cosine	topK	484	423	139	419
	shrink	555	936	127	235
	similarity	cosine	cosine	cosine	cosine
	normalize	False	True	True	False
	feature weighting	none	TF-IDF	none	TF-IDF
ItemKNN CF dice	topK	472	540	610	760
	shrink	292	61	402	991
	similarity	dice	dice	dice	dice
	normalize	False	False	False	True
ItemKNN CF jaccard	topK	114	612	548	754
	shrink	784	93	679	378
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	True	True	False	True
ItemKNN CF asymmetric	topK	700	900	848	1000
	shrink	430	1000	797	0
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	1.5472	0.0000	0.1235	0.0000
	feature weighting	TF-IDF	TF-IDF	BM25	none
ItemKNN CF tversky	topK	831	728	317	749
	shrink	810	44	32	0
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	0.6361	1.4249	0.9626	0.0000
	tversky beta	1.4516	1.0858	1.8163	2.0000

Table 20. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	CiteULike-a P=1	CiteULike-a P=10	CiteULike-t P=1	CiteULike-t P=10
$P^3\alpha$	topK	688	662	314	961
	alpha	1.1735	0.5112	0.7234	0.3851
	normalize similarity	True	False	False	False
$RP^3\beta$	topK	54	710	537	1000
	alpha	1.1242	0.0000	0.4656	0.8688
	beta	1.3282	0.0000	0.2366	0.0000
	normalize similarity	True	True	True	True
$EASE^R$	l2 norm	1.25E+06	6.98E+06	8.80E+02	5.41E+03
SLIM BPR	topK	402	458	537	818
	epochs	45	160	50	135
	symmetric	False	False	False	False
	sgd mode	sgd	adagrad	adagrad	adagrad
	lambda i	2.35E-03	1.00E-05	1.44E-03	1.00E-02
	lambda j	7.93E-03	1.00E-05	1.09E-04	1.00E-02
	learning rate	2.65E-04	1.00E-04	1.58E-04	1.00E-04
SLIMElasticNet	topK	795	450	644	949
	l1 ratio	1.72E-01	2.51E-04	1.23E-02	3.61E-05
	alpha	0.4724	0.0179	0.8273	1.0000
MF BPR	sgd mode	adam	adam	adagrad	adagrad
	epochs	25	660	20	1005
	num factors	90	200	73	200
	batch size	64	256	16	64
	positive reg	7.61E-04	1.00E-02	1.27E-04	1.00E-02
	negative reg	6.05E-04	9.89E-03	3.37E-04	1.00E-02
	learning rate	6.15E-04	4.56E-03	1.93E-02	1.00E-01
MF FunkSVD	sgd mode	adagrad	adam	adam	adagrad
	epochs	45	500	35	485
	use bias	False	False	False	True
	batch size	128	128	256	8
	num factors	48	28	77	200
	item reg	2.36E-05	3.45E-03	2.22E-04	1.00E-02
	user reg	6.40E-04	9.10E-04	2.28E-04	1.00E-02
	learning rate	8.37E-02	3.98E-03	9.13E-04	1.00E-01
	negative quota	0.1630	0.1334	0.4428	0.5000
PureSVD	num factors	284	350	350	350
NMF	num factors	245	188	127	301
	solver	mult. update	mult. update	mult. update	coord. descent
	init type	nndsvda	nndsvda	random	random
	beta loss	kullback-leibler	frobenius	kullback-leibler	frobenius
iALS	num factors	195	50	195	49
	confidence scaling	log	log	linear	log
	alpha	34.4360	50.0000	16.8297	50.0000
	epsilon	0.0055	0.0010	3.4947	0.0032
	reg	3.02E-04	1.00E-05	2.90E-04	1.00E-02
	epochs	5	60	5	105

Table 21. Hyperparameter values for our content based KNN baselines on all datasets.

Algorithm	Hyperparameter	CiteULike-a P=1	CiteULike-a P=10	CiteULike-t P=1	CiteULike-t P=10
ItemKNN CBF cosine	topK	5	849	692	563
	shrink	0	825	955	50
	similarity	cosine	cosine	cosine	cosine
	normalize	True	True	True	True
	feature weighting	none	BM25	BM25	TF-IDF
ItemKNN CBF dice	topK	5	571	626	636
	shrink	0	0	474	7
	similarity	dice	dice	dice	dice
	normalize	True	True	True	True
ItemKNN CBF jaccard	topK	13	527	429	543
	shrink	637	0	736	9
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	True	False	True	False
ItemKNN CBF asymmetric	topK	10	801	219	976
	shrink	14	1000	895	92
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	1.7300	0.4022	1.3276	0.5989
	feature weighting	TF-IDF	BM25	TF-IDF	TF-IDF
ItemKNN CBF tversky	topK	5	572	849	1000
	shrink	1000	0	491	0
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	0.0000	2.0000	1.4789	2.0000
	tversky beta	2.0000	2.0000	1.7951	2.0000

Table 22. Hyperparameter values for our hybrid KNN baselines on all datasets.

Algorithm	Hyperparameter	CiteULike-a P=1	CiteULike-a P=10	CiteULike-t P=1	CiteULike-t P=10
ItemKNN CFCBF cosine	topK	19	807	962	1000
	shrink	140	1000	151	1000
	similarity	cosine	cosine	cosine	cosine
	normalize	True	False	True	False
	feature weighting	BM25	BM25	TF-IDF	TF-IDF
	ICM weight	0.0101	1.1447	3.7971	1.5675
ItemKNN CFCBF dice	topK	7	492	918	332
	shrink	194	50	944	1000
	similarity	dice	dice	dice	dice
	normalize	False	False	False	False
	ICM weight	0.8195	72.9657	0.5285	0.0100
ItemKNN CFCBF jaccard	topK	34	554	418	347
	shrink	51	0	708	1000
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	True	True	False	True
	ICM weight	2.1492	0.0100	0.0121	100.0000
ItemKNN CFCBF asymmetric	topK	26	976	342	1000
	shrink	22	1000	252	1000
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	0.1370	0.0000	1.5682	0.0000
	feature weighting	BM25	TF-IDF	BM25	BM25
	ICM weight	0.0145	1.1144	0.0119	6.7370
ItemKNN CFCBF tversky	topK	59	585	530	283
	shrink	991	0	733	672
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	1.7260	1.3555	1.3336	0.0000
	tversky beta	0.6061	2.0000	0.8886	2.0000
	ICM weight	27.7050	100.0000	1.1171	0.0100

Table 23. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	CiteULike-a P=1	CiteULike-a P=10	CiteULike-t P=1	CiteULike-t P=10
CVAE	epochs	5	35	5	60
	learning rate vae	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	learning rate cvae	1.00E-03	1.00E-03	1.00E-03	1.00E-03
	num factors	50	50	50	50
	dimensions vae	[200, 100]	[200, 100]	[200, 100]	[200, 100]
	epochs vae	[50, 50]	[50, 50]	[50, 50]	[50, 50]
	batch size	128	128	128	128
	lambda u	1.00E-01	1.00E-01	1.00E-01	1.00E-01
	lambda v	1.00E+01	1.00E+01	1.00E+01	1.00E+01
	lambda r	1.00E+00	1.00E+00	1.00E+00	1.00E+00
	a	1	1	1	1
	b	0.0100	0.0100	0.0100	0.0100
	M	300	300	300	300
CDL	para lv	10	10	10	10
	para lu	1	1	1	1
	para ln	1000.0000	1000.0000	1000.0000	1000.0000
	batch size	128	128	128	128
	epoch sdae	200	200	200	200
	epoch dae	200	200	200	200

Table 24. Comparison of the computation time for the different algorithms.

	CiteULike-a P=1		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	15.06 [sec]	369
TopPop	0.02 [sec]	15.06 [sec]	369
UserKNN CF cosine	0.17 ± 0.02 [sec]	14.92 [sec]	372
UserKNN CF dice	0.17 ± 0.01 [sec]	15.25 [sec]	364
UserKNN CF jaccard	0.18 ± 0.01 [sec]	14.90 [sec]	372
UserKNN CF asymmetric	0.19 ± 0.00 [sec]	15.04 [sec]	369
UserKNN CF tversky	0.20 ± 0.01 [sec]	14.92 [sec]	372
ItemKNN CF cosine	1.10 ± 0.13 [sec]	14.92 [sec]	372
ItemKNN CF dice	1.16 ± 0.01 [sec]	14.97 [sec]	371
ItemKNN CF jaccard	1.20 ± 0.01 [sec]	14.82 [sec]	374
ItemKNN CF asymmetric	1.31 ± 0.02 [sec]	14.90 [sec]	372
ItemKNN CF tversky	1.42 ± 0.01 [sec]	14.93 [sec]	372
$P^3\alpha$	4.04 ± 0.09 [sec]	14.90 [sec]	372
$RP^3\beta$	4.11 ± 0.03 [sec]	14.86 [sec]	374
$EASE^R$	105.21 [sec] / 1.75 ± 0.04 [min]	14.56 [sec]	381
SLIM BPR	28.74 ± 8.04 [sec]	14.85 ± 0.14 [sec]	371
SLIMElasticNet	574.75 [sec] / 9.58 ± 0.11 [min]	17.19 [sec]	323
MF BPR	47.23 ± 71.90 [sec]	16.61 [sec]	334
MF FunkSVD	37.78 ± 39.27 [sec]	17.44 ± 0.36 [sec]	314
PureSVD	0.74 ± 0.44 [sec]	15.48 [sec]	359
NMF	19.72 ± 25.84 [sec]	16.45 ± 0.15 [sec]	340
iALS	100.51 [sec] / 1.68 ± 0.89 [min]	16.76 ± 0.13 [sec]	333
ItemKNN CBF cosine	7.75 ± 0.62 [sec]	14.41 ± 0.67 [sec]	405
ItemKNN CBF dice	8.01 ± 0.62 [sec]	14.27 ± 0.72 [sec]	403
ItemKNN CBF jaccard	7.98 ± 0.59 [sec]	14.42 ± 0.63 [sec]	402
ItemKNN CBF asymmetric	7.94 ± 0.47 [sec]	14.28 ± 0.53 [sec]	401
ItemKNN CBF tversky	8.24 ± 0.59 [sec]	14.31 ± 0.52 [sec]	408
ItemKNN CFCBF cosine	7.86 ± 0.55 [sec]	14.40 ± 0.80 [sec]	411
ItemKNN CFCBF dice	7.99 ± 0.58 [sec]	14.54 ± 0.70 [sec]	404
ItemKNN CFCBF jaccard	8.03 ± 0.57 [sec]	14.55 ± 0.47 [sec]	394
ItemKNN CFCBF asymmetric	8.14 ± 0.59 [sec]	14.39 ± 0.65 [sec]	412
ItemKNN CFCBF tversky	8.22 ± 0.54 [sec]	14.70 ± 0.59 [sec]	396
CVAE	2151.48 [sec] / 35.86 [min]	23.07 [sec]	241
CDL	5461.42 [sec] / 1.52 [hour]	17.32 [sec]	321

Table 25. Comparison of the computation time for the different algorithms.

	CiteULike-a P=10		
	Train time	Recommendation Time	[usr/s]
Random	0.02 [sec]	14.45 [sec]	356
TopPop	0.00 [sec]	13.93 [sec]	369
UserKNN CF cosine	0.25 ± 0.03 [sec]	14.19 ± 0.09 [sec]	363
UserKNN CF dice	0.26 ± 0.01 [sec]	14.12 ± 0.09 [sec]	364
UserKNN CF jaccard	0.26 ± 0.01 [sec]	14.29 ± 0.11 [sec]	358
UserKNN CF asymmetric	0.27 ± 0.01 [sec]	14.15 ± 0.07 [sec]	361
UserKNN CF tversky	0.29 ± 0.01 [sec]	14.08 ± 0.05 [sec]	365
ItemKNN CF cosine	1.38 ± 0.07 [sec]	14.16 ± 0.04 [sec]	362
ItemKNN CF dice	1.37 ± 0.02 [sec]	14.13 ± 0.04 [sec]	364
ItemKNN CF jaccard	1.40 ± 0.02 [sec]	14.10 ± 0.02 [sec]	364
ItemKNN CF asymmetric	1.49 ± 0.02 [sec]	14.13 ± 0.05 [sec]	362
ItemKNN CF tversky	1.63 ± 0.02 [sec]	14.18 ± 0.09 [sec]	359
$P^3\alpha$	4.36 ± 0.05 [sec]	14.26 ± 0.14 [sec]	364
$RP^3\beta$	4.54 ± 0.09 [sec]	14.24 ± 0.05 [sec]	362
$EASE^R$	107.59 [sec] / 1.79 ± 0.09 [min]	14.36 ± 0.04 [sec]	359
SLIM BPR	241.65 [sec] / 4.03 ± 1.30 [min]	14.46 ± 0.14 [sec]	356
SLIMElasticNet	651.80 [sec] / 10.86 ± 0.57 [min]	13.86 ± 0.19 [sec]	367
MF BPR	717.46 [sec] / 11.96 ± 8.87 [min]	15.18 ± 0.48 [sec]	338
MF FunkSVD	546.76 [sec] / 9.11 ± 6.29 [min]	14.83 ± 0.33 [sec]	350
PureSVD	1.29 ± 0.54 [sec]	15.01 ± 0.57 [sec]	347
NMF	184.83 [sec] / 3.08 ± 3.41 [min]	15.62 ± 0.19 [sec]	328
iALS	325.86 [sec] / 5.43 ± 3.66 [min]	15.55 ± 0.18 [sec]	326
ItemKNN CBF cosine	8.25 ± 0.60 [sec]	14.59 ± 0.24 [sec]	346
ItemKNN CBF dice	8.36 ± 0.40 [sec]	14.33 ± 0.13 [sec]	358
ItemKNN CBF jaccard	8.33 ± 0.42 [sec]	14.55 ± 0.16 [sec]	353
ItemKNN CBF asymmetric	8.61 ± 0.52 [sec]	14.66 ± 0.26 [sec]	347
ItemKNN CBF tversky	8.66 ± 0.41 [sec]	14.41 ± 0.12 [sec]	355
ItemKNN CFCBF cosine	8.47 ± 0.54 [sec]	14.32 ± 0.32 [sec]	355
ItemKNN CFCBF dice	8.49 ± 0.41 [sec]	14.23 ± 0.20 [sec]	360
ItemKNN CFCBF jaccard	8.50 ± 0.41 [sec]	14.23 ± 0.10 [sec]	357
ItemKNN CFCBF asymmetric	8.59 ± 0.54 [sec]	14.22 ± 0.32 [sec]	356
ItemKNN CFCBF tversky	8.77 ± 0.45 [sec]	14.31 ± 0.20 [sec]	361
CVAE	4555.65 [sec] / 1.27 [hour]	21.33 [sec]	241
CDL	5443.56 [sec] / 1.51 [hour]	15.26 [sec]	337

Table 26. Comparison of the computation time for the different algorithms.

	CiteULike-t P=1		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	22.92 [sec]	347
TopPop	0.00 [sec]	22.42 [sec]	355
UserKNN CF cosine	0.33 ± 0.03 [sec]	21.79 [sec]	365
UserKNN CF dice	0.34 ± 0.01 [sec]	21.92 [sec]	363
UserKNN CF jaccard	0.35 ± 0.01 [sec]	21.82 [sec]	364
UserKNN CF asymmetric	0.37 ± 0.01 [sec]	21.68 [sec]	367
UserKNN CF tversky	0.40 ± 0.01 [sec]	21.71 [sec]	366
ItemKNN CF cosine	2.42 ± 0.35 [sec]	21.79 [sec]	365
ItemKNN CF dice	2.59 ± 0.02 [sec]	21.84 [sec]	364
ItemKNN CF jaccard	2.68 ± 0.02 [sec]	21.71 [sec]	366
ItemKNN CF asymmetric	2.93 ± 0.03 [sec]	21.75 [sec]	365
ItemKNN CF tversky	3.21 ± 0.02 [sec]	21.87 [sec]	363
$P^3\alpha$	10.31 ± 0.07 [sec]	21.70 [sec]	366
$RP^3\beta$	10.26 ± 0.07 [sec]	21.73 [sec]	366
$EASE^R$	328.17 [sec] / 5.47 ± 2.29 [min]	15.31 ± 9.68 [sec]	939
SLIM BPR	108.13 [sec] / 1.80 ± 0.55 [min]	22.03 ± 0.02 [sec]	361
SLIMElasticNet	1223.53 [sec] / 20.39 ± 0.20 [min]	21.75 [sec]	365
MF BPR	158.20 [sec] / 2.64 ± 3.88 [min]	25.31 ± 0.10 [sec]	315
MF FunkSVD	101.31 [sec] / 1.69 ± 1.52 [min]	25.15 ± 0.07 [sec]	315
PureSVD	1.53 ± 0.65 [sec]	22.63 ± 0.22 [sec]	347
NMF	18.22 ± 45.02 [sec]	24.81 [sec]	320
iALS	118.47 [sec] / 1.97 ± 1.22 [min]	25.19 ± 0.12 [sec]	314
ItemKNN CBF cosine	5.86 ± 1.07 [sec]	20.60 [sec]	386
ItemKNN CBF dice	6.12 ± 0.97 [sec]	20.89 [sec]	381
ItemKNN CBF jaccard	6.18 ± 0.97 [sec]	20.93 [sec]	380
ItemKNN CBF asymmetric	6.36 ± 1.04 [sec]	20.34 [sec]	391
ItemKNN CBF tversky	6.70 ± 0.94 [sec]	21.09 [sec]	377
ItemKNN CFCBF cosine	5.84 ± 1.01 [sec]	20.89 [sec]	380
ItemKNN CFCBF dice	6.12 ± 0.94 [sec]	20.95 [sec]	379
ItemKNN CFCBF jaccard	6.17 ± 0.92 [sec]	20.62 [sec]	385
ItemKNN CFCBF asymmetric	6.38 ± 1.02 [sec]	19.40 [sec]	410
ItemKNN CFCBF tversky	6.71 ± 0.94 [sec]	20.67 [sec]	385
CVAE	3560.74 [sec] / 59.35 [min]	31.19 [sec]	255
CDL	22823.11 [sec] / 6.34 [hour]	24.51 [sec]	324

Table 27. Comparison of the computation time for the different algorithms.

	CiteULike-t P=10		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	7.69 [sec]	338
TopPop	0.00 [sec]	7.51 [sec]	346
UserKNN CF cosine	0.40 ± 0.04 [sec]	7.48 ± 0.02 [sec]	348
UserKNN CF dice	0.41 ± 0.01 [sec]	7.52 ± 0.05 [sec]	346
UserKNN CF jaccard	0.42 ± 0.01 [sec]	7.51 ± 0.01 [sec]	346
UserKNN CF asymmetric	0.45 ± 0.01 [sec]	7.50 ± 0.11 [sec]	343
UserKNN CF tversky	0.48 ± 0.01 [sec]	7.49 ± 0.01 [sec]	346
ItemKNN CF cosine	2.17 ± 0.46 [sec]	7.51 ± 0.03 [sec]	346
ItemKNN CF dice	3.01 ± 0.06 [sec]	7.47 ± 0.02 [sec]	349
ItemKNN CF jaccard	3.10 ± 0.07 [sec]	7.40 ± 0.11 [sec]	347
ItemKNN CF asymmetric	3.35 ± 0.07 [sec]	7.53 ± 0.07 [sec]	341
ItemKNN CF tversky	3.65 ± 0.09 [sec]	7.47 ± 0.01 [sec]	348
$P^3\alpha$	10.63 ± 0.07 [sec]	7.58 [sec]	343
$RP^3\beta$	10.71 ± 0.10 [sec]	7.47 ± 0.08 [sec]	345
$EASE^R$	383.01 [sec] / 6.38 ± 2.54 [min]	8.09 [sec]	321
SLIM BPR	529.68 [sec] / 8.83 ± 4.30 [min]	7.65 ± 0.10 [sec]	337
SLIMElasticNet	1454.18 [sec] / 24.24 ± 1.19 [min]	7.46 ± 0.19 [sec]	339
MF BPR	1143.88 [sec] / 19.06 ± 13.39 [min]	8.27 ± 0.14 [sec]	308
MF FunkSVD	1004.38 [sec] / 16.74 ± 8.98 [min]	8.59 ± 0.09 [sec]	299
PureSVD	2.03 ± 0.80 [sec]	7.74 ± 0.01 [sec]	336
NMF	478.36 [sec] / 7.97 ± 10.31 [min]	8.57 ± 0.15 [sec]	300
iALS	570.10 [sec] / 9.50 ± 6.63 [min]	8.57 ± 0.02 [sec]	303
ItemKNN CBF cosine	6.24 ± 0.87 [sec]	7.58 ± 0.07 [sec]	345
ItemKNN CBF dice	6.34 ± 0.62 [sec]	7.62 ± 0.02 [sec]	340
ItemKNN CBF jaccard	6.43 ± 0.64 [sec]	7.62 ± 0.17 [sec]	339
ItemKNN CBF asymmetric	7.03 ± 0.77 [sec]	7.61 ± 0.20 [sec]	335
ItemKNN CBF tversky	7.04 ± 0.67 [sec]	7.69 ± 0.16 [sec]	333
ItemKNN CFCBF cosine	6.38 ± 0.76 [sec]	7.71 ± 0.22 [sec]	329
ItemKNN CFCBF dice	6.33 ± 0.65 [sec]	7.57 ± 0.11 [sec]	346
ItemKNN CFCBF jaccard	6.38 ± 0.65 [sec]	7.54 ± 0.04 [sec]	346
ItemKNN CFCBF asymmetric	7.31 ± 0.76 [sec]	7.65 ± 0.32 [sec]	317
ItemKNN CFCBF tversky	6.87 ± 0.60 [sec]	7.49 ± 0.05 [sec]	346
CVAE	9969.70 [sec] / 2.77 [hour]	11.68 [sec]	222
CDL	22343.75 [sec] / 6.21 [hour]	8.65 [sec]	300

F RECSYS: SPECTRAL COLLABORATIVE FILTERING

Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 28 and 29. The results of our evaluation can be seen in Table 30 (Amazon Instant Video, Hetrec) and Table 31 (Movielens 1M original split and our split). The corresponding optimal hyperparameters are reported in Table 32 (collaborative KNNs), Table 33 (non-neural machine learning and graph based) and 34 (SpectralCF original hyperparameters and ours).

Lastly, the time required to train and evaluate the models is reported in Table 35 (Amazon Instant Video), Table 36 (Hetrec), Table 36 (Movielens 1M original split) and Table 36 (Movielens 1M our split).

Table 28. Dataset characteristics.

Dataset	Interactions	Items	Users	Density
Movielens 1M	226 K	3706	6040	1.01%
Hetrec	71 K	10109	2113	0.33%
Amazon Instant Video	22 K	5860	3113	0.12%

Table 29. The statistics compare the popularity bias of the two splits of Movielens 1M we report the results of, the original one provided by the authors and the split generated by us following the description provided in the paper. The three rows refer to the statistics of the dataset as a whole and those of the train and test data split. In a truly random data split the statistics of train and test data should mirror closely those of the full dataset. It is possible to see that the original test data (values in bold) has very different statistical properties than the original full dataset, hinting at a possible error in the splitting procedure. *Kendall Tau* counts the number of pairwise disagreements between two ranking lists, its result is the percentage of item pairs whose ordering is discordant between the two splits. This metric highlight how inconsistent is the original test data with respect to the original train data.

	Max pop	Avg pop	Gini Index	Kendall Tau	Shannon
	Movielens original				
Full data	1963.00	61.08	0.78	1.00	9.99
Train data	1936.00	48.37	0.79	0.87	9.89
Test data	**1361.00**	12.71	**0.92**	**0.44**	**8.4**9
	Movielens ours				
Full data	1963.00	58.08	0.79	1.00	9.99
Train data	1575.00	46.44	0.79	0.97	9.99
Test data	388.00	11.64	0.80	0.85	9.93

Table 30. Experimental results for SpectralCF on the metrics and cutoffs reported in the original paper.

	Amazon Instant Video									
	REC@20	MAP@20	REC@40	MAP@40	REC@60	MAP@60	REC@80	MAP@80	REC@100	MAP@100
Random	0.0047	0.0006	0.0099	0.0008	0.0150	0.0009	0.0195	0.0010	0.0240	0.0010
TopPop	**0.1134**	**0.0288**	**0.1687**	**0.0308**	0.2067	**0.0316**	**0.2448**	**0.0322**	**0.2716**	**0.0326**
UserKNN CF cosine	**0.2853**	**0.1200**	**0.3559**	**0.1228**	**0.3986**	**0.1238**	**0.4297**	**0.1243**	**0.4527**	**0.1246**
UserKNN CF dice	**0.2845**	**0.1198**	**0.3550**	**0.1225**	**0.3989**	**0.1236**	**0.4294**	**0.1240**	**0.4520**	**0.1243**
UserKNN CF jaccard	**0.2850**	**0.1198**	**0.3544**	**0.1225**	**0.3991**	**0.1235**	**0.4282**	**0.1240**	**0.4515**	**0.1243**
UserKNN CF asymmetric	**0.2850**	**0.1201**	**0.3552**	**0.1228**	**0.3991**	**0.1239**	**0.4297**	**0.1244**	**0.4526**	**0.1247**
UserKNN CF tversky	**0.2856**	**0.1196**	**0.3544**	**0.1223**	**0.3991**	**0.1233**	**0.4286**	**0.1238**	**0.4515**	**0.1241**
ItemKNN CF cosine	**0.2858**	**0.1209**	**0.3535**	**0.1236**	**0.3985**	**0.1246**	**0.4303**	**0.1252**	**0.4528**	**0.1255**
ItemKNN CF dice	**0.2968**	**0.1290**	**0.3628**	**0.1316**	**0.4010**	**0.1325**	**0.4262**	**0.1329**	**0.4487**	**0.1332**
ItemKNN CF jaccard	**0.2957**	**0.1296**	**0.3628**	**0.1322**	**0.3996**	**0.1331**	**0.4250**	**0.1335**	**0.4482**	**0.1338**
ItemKNN CF asymmetric	**0.3044**	**0.1309**	**0.3712**	**0.1336**	**0.4127**	**0.1346**	**0.4426**	**0.1351**	**0.4653**	**0.1354**
ItemKNN CF tversky	**0.2913**	**0.1195**	**0.3594**	**0.1221**	**0.4021**	**0.1231**	**0.4319**	**0.1236**	**0.4538**	**0.1239**
P3alpha	**0.3019**	**0.1276**	**0.3721**	**0.1304**	**0.4151**	**0.1314**	**0.4433**	**0.1319**	**0.4648**	**0.1322**
RP3beta	**0.3029**	**0.1354**	**0.3715**	**0.1382**	**0.4119**	**0.1391**	**0.4378**	**0.1396**	**0.4584**	**0.1398**
EASE R	**0.2897**	**0.1211**	**0.3579**	**0.1237**	**0.3959**	**0.1246**	**0.4233**	**0.1250**	**0.4418**	**0.1253**
SLIM BPR	**0.2973**	**0.1326**	**0.3671**	**0.1353**	**0.3993**	**0.1361**	**0.4279**	**0.1366**	**0.4501**	**0.1369**
SLIMElasticNet	**0.2882**	**0.1224**	**0.3576**	**0.1250**	**0.3966**	**0.1260**	**0.4256**	**0.1264**	**0.4482**	**0.1267**
MF BPR	**0.2320**	**0.0951**	**0.2925**	**0.0974**	**0.3340**	**0.0983**	**0.3678**	**0.0989**	**0.3921**	**0.0992**
MF FunkSVD	**0.1800**	**0.0484**	**0.2615**	**0.0516**	**0.3129**	**0.0527**	**0.3488**	**0.0533**	**0.3752**	**0.0536**
PureSVD	**0.1555**	**0.0533**	**0.2079**	**0.0553**	**0.2466**	**0.0561**	**0.2758**	**0.0566**	**0.3031**	**0.0569**
NMF	**0.1406**	**0.0569**	**0.1850**	**0.0586**	**0.2147**	**0.0592**	**0.2454**	**0.0597**	0.2654	**0.0600**
IALS	**0.2741**	**0.0951**	**0.3526**	**0.0981**	**0.4003**	**0.0993**	**0.4330**	**0.0998**	**0.4582**	**0.1002**
SpectralCF	0.1125	0.0245	0.1649	0.0264	0.2080	0.0274	0.2394	0.0278	0.2700	0.0282
SpectralCF article default	0.1063	0.0255	0.1542	0.0273	0.1969	0.0282	0.2332	0.0288	0.2670	0.0292

	Hetrec									
	REC@20	MAP@20	REC@40	MAP@40	REC@60	MAP@60	REC@80	MAP@80	REC@100	MAP@100
Random	0.0014	0.0003	0.0032	0.0004	0.0050	0.0004	0.0071	0.0004	0.0100	0.0005
TopPop	**0.2044**	**0.0639**	**0.2918**	**0.0684**	**0.3484**	**0.0710**	**0.3927**	**0.0726**	**0.4291**	**0.0737**
UserKNN CF cosine	**0.2649**	**0.1081**	**0.3604**	**0.1132**	**0.4139**	**0.1159**	**0.4576**	**0.1177**	**0.4927**	**0.1189**
UserKNN CF dice	**0.2627**	**0.1081**	**0.3528**	**0.1132**	**0.4061**	**0.1158**	**0.4522**	**0.1176**	**0.4909**	**0.1189**
UserKNN CF jaccard	**0.2617**	**0.1077**	**0.3514**	**0.1127**	**0.4050**	**0.1153**	**0.4491**	**0.1170**	**0.4900**	**0.1184**
UserKNN CF asymmetric	**0.2667**	**0.1088**	**0.3606**	**0.1139**	**0.4142**	**0.1166**	**0.4571**	**0.1184**	**0.4934**	**0.1197**
UserKNN CF tversky	**0.2617**	**0.1079**	**0.3507**	**0.1129**	**0.4050**	**0.1156**	**0.4494**	**0.1173**	**0.4901**	**0.1187**
ItemKNN CF cosine	**0.2682**	**0.1092**	**0.3533**	**0.1136**	**0.4142**	**0.1165**	**0.4575**	**0.1182**	**0.4952**	**0.1196**
ItemKNN CF dice	**0.2549**	**0.1041**	**0.3464**	**0.1088**	**0.4061**	**0.1115**	**0.4504**	**0.1132**	**0.4860**	**0.1145**
ItemKNN CF jaccard	**0.2537**	**0.1051**	**0.3434**	**0.1098**	**0.4017**	**0.1125**	**0.4473**	**0.1143**	**0.4852**	**0.1156**
ItemKNN CF asymmetric	**0.2703**	**0.1003**	**0.3610**	**0.1058**	**0.4184**	**0.1087**	**0.4637**	**0.1107**	**0.4943**	**0.1121**
ItemKNN CF tversky	**0.2632**	**0.1038**	**0.3554**	**0.1091**	**0.4174**	**0.1121**	**0.4588**	**0.1139**	**0.4944**	**0.1153**
P3alpha	**0.2572**	**0.0981**	**0.3532**	**0.1037**	**0.4139**	**0.1067**	**0.4608**	**0.1085**	**0.5002**	**0.1099**
RP3beta	**0.2688**	**0.1058**	**0.3628**	**0.1114**	**0.4279**	**0.1146**	**0.4714**	**0.1165**	**0.5073**	**0.1178**
EASE R	**0.2707**	**0.1158**	**0.3580**	**0.1207**	**0.4188**	**0.1235**	**0.4634**	**0.1254**	**0.4945**	**0.1267**
SLIM BPR	**0.2566**	**0.1035**	**0.3451**	**0.1086**	**0.4016**	**0.1114**	**0.4452**	**0.1130**	**0.4840**	**0.1144**
SLIMElasticNet	**0.2791**	**0.1214**	**0.3634**	**0.1261**	**0.4226**	**0.1291**	**0.4637**	**0.1311**	**0.4976**	**0.1324**
MF BPR	**0.1820**	**0.0586**	**0.2776**	**0.0638**	**0.3312**	**0.0662**	**0.3752**	**0.0678**	**0.4073**	**0.0689**
MF FunkSVD	**0.2010**	**0.0540**	**0.2976**	**0.0597**	**0.3575**	**0.0623**	**0.3988**	**0.0639**	**0.4300**	**0.0649**
PureSVD	**0.2560**	**0.1087**	**0.3438**	**0.1130**	**0.3995**	**0.1158**	**0.4417**	**0.1175**	**0.4823**	**0.1190**
NMF	**0.2065**	**0.0865**	**0.2834**	**0.0903**	**0.3388**	**0.0931**	**0.3790**	**0.0947**	**0.4179**	**0.0960**
IALS	**0.2726**	**0.1104**	**0.3660**	**0.1163**	**0.4289**	**0.1195**	**0.4842**	**0.1217**	**0.5188**	**0.1232**
SpectralCF	0.1769	0.0539	0.2595	0.0584	0.3224	0.0611	0.3674	0.0627	0.3949	0.0635
SpectralCF article default	0.1450	0.0320	0.2261	0.0358	0.2849	0.0381	0.3366	0.0397	0.3866	0.0410

Table 31. Experimental results for SpectralCF on the metrics and cutoffs reported in the original paper.

	Movielens 1M original									
	REC@20	MAP@20	REC@40	MAP@40	REC@60	MAP@60	REC@80	MAP@80	REC@100	MAP@100
Random	0.0052	0.0010	0.0107	0.0011	0.0156	0.0012	0.0209	0.0013	0.0267	0.0014
TopPop	0.0382	0.0065	0.0969	0.0092	0.1207	0.0101	0.1651	0.0113	0.2286	0.0127
UserKNN CF cosine	0.0917	0.0193	0.1558	0.0226	0.2100	0.0246	0.2514	0.0258	0.2868	0.0267
UserKNN CF dice	0.0993	0.0214	0.1683	0.0250	0.2223	0.0271	0.2623	0.0283	0.2978	0.0292
UserKNN CF jaccard	0.0998	0.0211	0.1691	0.0247	0.2241	0.0268	0.2659	0.0280	0.3012	0.0289
UserKNN CF asymmetric	0.0982	0.0214	0.1644	0.0248	0.2165	0.0268	0.2578	0.0280	0.2943	0.0290
UserKNN CF tversky	0.0999	0.0208	0.1687	0.0244	0.2239	0.0265	0.2672	0.0278	0.3021	0.0287
ItemKNN CF cosine	0.0676	0.0143	0.1217	0.0170	0.1632	0.0185	0.2004	0.0195	0.2326	0.0203
ItemKNN CF dice	0.0673	0.0154	0.1226	0.0181	0.1679	0.0197	0.2071	0.0208	0.2443	0.0218
ItemKNN CF jaccard	0.0670	0.0146	0.1218	0.0173	0.1664	0.0189	0.2051	0.0200	0.2438	0.0209
ItemKNN CF asymmetric	0.0988	0.0215	0.1745	0.0256	0.2311	0.0279	0.2783	0.0296	0.3189	0.0308
ItemKNN CF tversky	0.0730	0.0147	0.1375	0.0179	0.1908	0.0199	0.2384	0.0213	0.2798	0.0224
P3alpha	0.1218	0.0256	0.2072	0.0306	0.2696	0.0335	0.3174	0.0353	**0.3583**	0.0367
RP3beta	0.0916	0.0192	0.1628	0.0230	0.2216	0.0254	0.2738	0.0271	0.3171	0.0284
EASE R	0.0914	0.0184	0.1531	0.0216	0.2010	0.0234	0.2398	0.0246	0.2736	0.0254
SLIM BPR	0.1292	0.0283	0.2090	0.0329	0.2687	0.0355	0.3140	0.0371	**0.3525**	0.0384
SLIMElasticNet	0.0915	0.0205	0.1521	0.0237	0.2014	0.0255	0.2392	0.0267	0.2692	0.0275
MF BPR	0.0863	0.0205	0.1532	0.0239	0.2062	0.0260	0.2518	0.0274	0.2874	0.0284
MF FunkSVD	0.1061	0.0262	0.1746	0.0301	0.2286	0.0323	0.2753	0.0339	0.3127	0.0351
PureSVD	0.0828	0.0172	0.1424	0.0204	0.1833	0.0219	0.2170	0.0229	0.2472	0.0236
NMF	0.0795	0.0199	0.1252	0.0223	0.1602	0.0236	0.1884	0.0245	0.2127	0.0251
IALS	0.0868	0.0188	0.1441	0.0218	0.1933	0.0235	0.2299	0.0245	0.2621	0.0252
SpectralCF	0.1567	0.0621	0.2099	0.0642	0.2475	0.0658	0.2911	0.0675	0.3354	0.0689
SpectralCF article default	**0.1849**	**0.0838**	**0.2376**	**0.0857**	**0.2808**	**0.0879**	**0.3248**	**0.0894**	0.3493	**0.0902**

	Movielens 1M ours									
	REC@20	MAP@20	REC@40	MAP@40	REC@60	MAP@60	REC@80	MAP@80	REC@100	MAP@100
Random	0.0060	0.0013	0.0115	0.0014	0.0166	0.0015	0.0224	0.0016	0.0274	0.0017
TopPop	**0.1892**	**0.0584**	**0.2788**	**0.0636**	**0.3356**	**0.0666**	**0.3834**	**0.0687**	0.4226	**0.0702**
UserKNN CF cosine	**0.2978**	**0.1195**	**0.4108**	**0.1280**	**0.4866**	**0.1329**	**0.5444**	**0.1361**	**0.5868**	**0.1382**
UserKNN CF dice	**0.2960**	**0.1185**	**0.4111**	**0.1270**	**0.4872**	**0.1319**	**0.5443**	**0.1351**	**0.5873**	**0.1372**
UserKNN CF jaccard	**0.3001**	**0.1201**	**0.4134**	**0.1285**	**0.4901**	**0.1335**	**0.5457**	**0.1367**	**0.5884**	**0.1388**
UserKNN CF asymmetric	**0.2880**	**0.1156**	**0.4016**	**0.1236**	**0.4785**	**0.1285**	**0.5361**	**0.1316**	**0.5820**	**0.1338**
UserKNN CF tversky	**0.2903**	**0.1161**	**0.4061**	**0.1244**	**0.4818**	**0.1293**	**0.5394**	**0.1325**	**0.5842**	**0.1346**
ItemKNN CF cosine	**0.2929**	**0.1154**	**0.4067**	**0.1236**	**0.4843**	**0.1287**	**0.5401**	**0.1318**	**0.5829**	**0.1340**
ItemKNN CF dice	**0.2747**	**0.1053**	**0.3770**	**0.1125**	**0.4519**	**0.1170**	**0.5070**	**0.1200**	**0.5556**	**0.1222**
ItemKNN CF jaccard	**0.2731**	**0.1051**	**0.3783**	**0.1126**	**0.4539**	**0.1172**	**0.5099**	**0.1202**	**0.5582**	**0.1224**
ItemKNN CF asymmetric	**0.2876**	**0.1134**	**0.4000**	**0.1213**	**0.4768**	**0.1263**	**0.5367**	**0.1295**	**0.5820**	**0.1317**
ItemKNN CF tversky	**0.2760**	**0.1043**	**0.3877**	**0.1122**	**0.4659**	**0.1175**	**0.5250**	**0.1209**	**0.5713**	**0.1232**
P3alpha	**0.2939**	**0.1141**	**0.4150**	**0.1233**	**0.4900**	**0.1285**	**0.5463**	**0.1318**	**0.5903**	**0.1342**
RP3beta	**0.2737**	**0.1044**	**0.3879**	**0.1124**	**0.4664**	**0.1173**	**0.5234**	**0.1206**	**0.5726**	**0.1230**
EASE R	**0.2967**	**0.1176**	**0.4118**	**0.1261**	**0.4855**	**0.1312**	**0.5402**	**0.1345**	**0.5854**	**0.1367**
SLIM BPR	**0.2886**	**0.1086**	**0.4048**	**0.1170**	**0.4813**	**0.1219**	**0.5362**	**0.1249**	**0.5782**	**0.1269**
SLIMElasticNet	**0.3069**	**0.1265**	**0.4246**	**0.1356**	**0.5010**	**0.1410**	**0.5564**	**0.1443**	**0.6001**	**0.1466**
MF BPR	**0.2616**	**0.0956**	**0.3662**	**0.1028**	**0.4377**	**0.1071**	**0.4890**	**0.1097**	**0.5307**	**0.1116**
MF FunkSVD	**0.2684**	**0.0875**	**0.3890**	**0.0963**	**0.4663**	**0.1015**	**0.5252**	**0.1049**	**0.5720**	**0.1072**
PureSVD	**0.2595**	**0.1008**	**0.3638**	**0.1083**	**0.4378**	**0.1131**	**0.4913**	**0.1161**	**0.5347**	**0.1182**
NMF	**0.2384**	**0.0908**	**0.3351**	**0.0972**	**0.4032**	**0.1014**	**0.4568**	**0.1041**	**0.4981**	**0.1060**
IALS	**0.3033**	**0.1183**	**0.4201**	**0.1273**	**0.4933**	**0.1326**	**0.5493**	**0.1360**	**0.5925**	**0.1383**
SpectralCF	0.1813	0.0533	0.2643	0.0581	0.3274	0.0613	0.3823	0.0635	0.4261	0.0651
SpectralCF article default	0.1785	0.0540	0.2590	0.0586	0.3232	0.0614	0.3689	0.0632	0.4101	0.0646

Table 32. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M ours	Movielens 1M original	Hetrec	Amazon Instant Video
UserKNN CF cosine	topK	418	365	464	800
	shrink	402	0	0	346
	similarity	cosine	cosine	cosine	cosine
	normalize	True	True	True	False
	feature weighting	TF-IDF	TF-IDF	none	TF-IDF
UserKNN CF dice	topK	383	276	428	484
	shrink	0	1	1	940
	similarity	dice	dice	dice	dice
	normalize	False	True	True	False
UserKNN CF jaccard	topK	300	337	456	444
	shrink	0	0	0	303
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	False	True	False	True
UserKNN CF asymmetric	topK	734	369	441	855
	shrink	0	134	0	19
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	0.4193	0.6047	0.5026	0.7882
	feature weighting	TF-IDF	TF-IDF	TF-IDF	none
UserKNN CF tversky	topK	516	377	449	476
	shrink	0	0	0	806
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	1.2079	2.0000	2.0000	1.3499
	tversky beta	2.0000	2.0000	2.0000	1.7078
ItemKNN CF cosine	topK	197	615	322	998
	shrink	0	0	1000	21
	similarity	cosine	cosine	cosine	cosine
	normalize	True	True	True	False
	feature weighting	TF-IDF	TF-IDF	TF-IDF	TF-IDF
ItemKNN CF dice	topK	218	137	195	443
	shrink	2	0	33	172
	similarity	dice	dice	dice	dice
	normalize	True	False	False	False
ItemKNN CF jaccard	topK	158	135	222	290
	shrink	1	0	5	140
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	True	False	True	True
ItemKNN CF asymmetric	topK	269	1000	462	1000
	shrink	0	0	222	1000
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	0.3993	0.0466	0.0000	0.0000
	feature weighting	TF-IDF	TF-IDF	TF-IDF	TF-IDF
ItemKNN CF tversky	topK	48	143	142	1000
	shrink	77	0	23	1000
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	0.8429	0.4521	0.2786	0.0000
	tversky beta	1.7696	2.0000	1.3237	2.0000

Table 33. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M ours	Movielens 1M original	Hetrec	Amazon Instant Video
$P^3\alpha$	topK	350	332	901	1000
	alpha	0.6537	1.0075	0.7565	0.3705
	normalize similarity	True	True	False	False
$RP^3\beta$	topK	853	537	1000	442
	alpha	0.0000	0.7551	0.8163	0.6540
	beta	0.4098	0.5412	0.2099	0.0332
	normalize similarity	True	False	False	False
$EASE^R$	l2 norm	1.25E+03	1.72E+03	1.03E+03	3.06E+06
SLIM BPR	topK	329	1000	725	1000
	epochs	130	200	80	150
	symmetric	True	True	True	False
	sgd mode	sgd	adagrad	adagrad	adagrad
	lambda i	1.00E-02	1.00E-05	1.00E-05	1.00E-02
	lambda j	1.00E-02	1.00E-05	1.00E-05	1.00E-02
	learning rate	1.33E-02	1.00E-01	3.19E-04	1.00E-04
SLIMElasticNet	topK	642	747	602	862
	l1 ratio	1.89E-05	7.37E-05	1.58E-05	6.11E-05
	alpha	0.0490	0.0371	0.1354	0.5507
MF BPR	sgd mode	adagrad	adagrad	adagrad	adagrad
	epochs	790	445	190	500
	num factors	200	200	200	200
	batch size	512	32	64	1
	positive reg	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	negative reg	1.00E-05	1.00E-02	1.00E-02	1.00E-02
	learning rate	2.86E-02	1.00E-01	2.22E-02	1.00E-01
MF FunkSVD	sgd mode	adam	adam	adam	adam
	epochs	325	280	70	370
	use bias	True	False	True	False
	batch size	32	2	8	2
	num factors	19	8	98	13
	item reg	1.47E-04	1.28E-05	2.19E-05	6.87E-05
	user reg	1.88E-04	6.74E-04	6.92E-03	3.09E-04
	learning rate	2.45E-03	1.54E-03	4.73E-03	1.15E-02
	negative quota	0.2131	0.1045	0.4633	0.1323
PureSVD	num factors	16	15	9	33
NMF	num factors	9	20	22	37
	solver	coord. descent	mult. update	mult. update	mult. update
	init type	random	nndsvda	random	nndsvda
	beta loss	frobenius	kullback-leibler	frobenius	frobenius
iALS	num factors	24	22	11	26
	confidence scaling	log	log	linear	linear
	alpha	50.0000	1.7077	6.0056	50.0000
	epsilon	10.0000	0.0010	0.0010	0.0010
	reg	1.20E-04	1.00E-05	1.31E-03	1.00E-05
	epochs	20	75	45	50

Table 34. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Movielens 1M ours	Movielens 1M original	Hetrec	Amazon Instant Video
SpectralCF ours	batch size	2048	2048	512	1024
	embedding size	4	16	16	8
	decay	0.0306	0.0032	0.0018	0.0003
	learning rate	8.83E-04	7.00E-03	5.35E-03	9.68E-03
	k	2	3	2	3
	epochs	805	350	265	445
SpectralCF original article	epochs	600	410	185	425
	batch size	1024	1024	1024	1024
	embedding size	16	16	16	16
	decay	0.0010	0.0010	0.0010	0.0010
	k	3	3	3	3
	learning rate	1.00E-03	1.00E-03	1.00E-03	1.00E-03

Table 35. Comparison of the computation time for the different algorithms.

	Amazon Instant Video		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	15.23 [sec]	204
TopPop	0.00 [sec]	15.41 [sec]	202
UserKNN CF cosine	0.16 ± 0.01 [sec]	15.56 ± 0.04 [sec]	200
UserKNN CF dice	0.17 ± 0.00 [sec]	15.52 ± 0.03 [sec]	200
UserKNN CF jaccard	0.17 ± 0.00 [sec]	15.48 ± 0.02 [sec]	201
UserKNN CF asymmetric	0.17 ± 0.01 [sec]	15.41 ± 0.13 [sec]	201
UserKNN CF tversky	0.17 ± 0.00 [sec]	15.53 ± 0.03 [sec]	201
ItemKNN CF cosine	0.38 ± 0.04 [sec]	15.42 ± 0.09 [sec]	202
ItemKNN CF dice	0.40 ± 0.01 [sec]	15.53 ± 0.01 [sec]	201
ItemKNN CF jaccard	0.40 ± 0.01 [sec]	15.47 ± 0.05 [sec]	202
ItemKNN CF asymmetric	0.41 ± 0.01 [sec]	15.52 ± 0.02 [sec]	201
ItemKNN CF tversky	0.41 ± 0.01 [sec]	15.53 ± 0.04 [sec]	200
$P^3\alpha$	0.87 ± 0.03 [sec]	15.54 ± 0.07 [sec]	199
$RP^3\beta$	0.95 ± 0.04 [sec]	15.28 ± 0.17 [sec]	201
$EASE^R$	15.96 ± 0.03 [sec]	15.57 ± 0.17 [sec]	199
SLIM BPR	83.48 [sec] / 1.39 ± 0.59 [min]	15.66 ± 0.05 [sec]	199
SLIMElasticNet	51.52 ± 3.17 [sec]	15.62 ± 0.16 [sec]	198
MF BPR	225.64 [sec] / 3.76 ± 2.96 [min]	15.77 ± 0.20 [sec]	194
MF FunkSVD	85.76 [sec] / 1.43 ± 1.50 [min]	15.58 ± 0.16 [sec]	198
PureSVD	0.15 ± 0.19 [sec]	15.38 ± 0.02 [sec]	202
NMF	28.00 ± 44.31 [sec]	15.64 ± 0.14 [sec]	199
iALS	193.65 [sec] / 3.23 ± 2.87 [min]	15.73 ± 0.09 [sec]	198
SpectralCF	1118.55 [sec] / 18.64 ± 2.65 [min]	10.42 ± 0.21 [sec]	295
SpectralCF article default	1335.22 [sec] / 22.25 [min]	10.27 [sec]	303

Table 36. Comparison of the computation time for the different algorithms.

	Hetrec		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	10.21 [sec]	194
TopPop	0.00 [sec]	11.17 [sec]	177
UserKNN CF cosine	0.22 ± 0.03 [sec]	11.47 ± 0.06 [sec]	172
UserKNN CF dice	0.23 ± 0.03 [sec]	11.38 ± 0.10 [sec]	174
UserKNN CF jaccard	0.23 ± 0.04 [sec]	11.41 ± 0.03 [sec]	174
UserKNN CF asymmetric	0.23 ± 0.04 [sec]	11.44 ± 0.04 [sec]	173
UserKNN CF tversky	0.23 ± 0.04 [sec]	11.45 ± 0.03 [sec]	174
ItemKNN CF cosine	1.13 ± 0.09 [sec]	11.52 ± 0.05 [sec]	172
ItemKNN CF dice	1.13 ± 0.06 [sec]	11.34 ± 0.19 [sec]	174
ItemKNN CF jaccard	1.14 ± 0.06 [sec]	11.42 ± 0.04 [sec]	174
ItemKNN CF asymmetric	1.13 ± 0.08 [sec]	11.29 ± 0.44 [sec]	172
ItemKNN CF tversky	1.15 ± 0.07 [sec]	11.40 ± 0.06 [sec]	174
$P^3\alpha$	4.78 ± 0.66 [sec]	11.40 ± 0.07 [sec]	174
$RP^3\beta$	4.55 ± 0.99 [sec]	11.07 ± 0.63 [sec]	172
$EASE^R$	77.06 [sec] / 1.28 ± 0.00 [min]	11.53 ± 0.03 [sec]	171
SLIM BPR	130.28 [sec] / 2.17 ± 0.91 [min]	11.39 ± 0.07 [sec]	173
SLIMElasticNet	306.32 [sec] / 5.11 ± 0.21 [min]	11.30 ± 0.57 [sec]	173
MF BPR	124.76 [sec] / 2.08 ± 2.29 [min]	11.36 ± 0.34 [sec]	171
MF FunkSVD	91.33 [sec] / 1.52 ± 1.67 [min]	11.59 ± 0.20 [sec]	170
PureSVD	0.18 ± 0.23 [sec]	11.08 ± 0.20 [sec]	177
NMF	36.78 ± 66.11 [sec]	11.50 ± 0.12 [sec]	172
iALS	187.90 [sec] / 3.13 ± 5.58 [min]	11.45 ± 0.03 [sec]	172
SpectralCF	1704.87 [sec] / 28.41 ± 4.33 [min]	7.80 ± 0.19 [sec]	249
SpectralCF article default	2197.20 [sec] / 36.62 [min]	7.42 [sec]	267

Table 37. Comparison of the computation time for the different algorithms.

	Movielens 1M original		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	27.37 [sec]	200
TopPop	0.01 [sec]	28.35 [sec]	193
UserKNN CF cosine	1.54 ± 0.20 [sec]	29.21 ± 0.45 [sec]	187
UserKNN CF dice	1.53 ± 0.22 [sec]	29.04 ± 0.19 [sec]	189
UserKNN CF jaccard	1.51 ± 0.21 [sec]	29.09 ± 0.18 [sec]	189
UserKNN CF asymmetric	1.58 ± 0.24 [sec]	29.19 ± 0.08 [sec]	188
UserKNN CF tversky	1.54 ± 0.25 [sec]	29.07 ± 0.39 [sec]	188
ItemKNN CF cosine	0.47 ± 0.07 [sec]	29.08 ± 0.33 [sec]	188
ItemKNN CF dice	0.41 ± 0.06 [sec]	28.73 ± 0.15 [sec]	191
ItemKNN CF jaccard	0.42 ± 0.06 [sec]	28.93 ± 0.21 [sec]	191
ItemKNN CF asymmetric	0.49 ± 0.05 [sec]	29.26 ± 0.50 [sec]	184
ItemKNN CF tversky	0.43 ± 0.07 [sec]	28.95 ± 0.11 [sec]	190
$P^3\alpha$	2.31 ± 0.82 [sec]	29.54 ± 0.23 [sec]	186
$RP^3\beta$	2.66 ± 0.90 [sec]	29.35 ± 0.97 [sec]	186
$EASE^R$	5.07 ± 0.01 [sec]	28.77 ± 0.24 [sec]	189
SLIM BPR	218.79 [sec] / 3.65 ± 1.84 [min]	29.69 ± 0.13 [sec]	185
SLIMElasticNet	60.10 [sec] / 1.00 ± 0.16 [min]	28.88 ± 0.16 [sec]	190
MF BPR	431.40 [sec] / 7.19 ± 5.28 [min]	29.09 ± 0.09 [sec]	188
MF FunkSVD	370.25 [sec] / 6.17 ± 7.29 [min]	29.05 ± 0.52 [sec]	182
PureSVD	0.27 ± 0.33 [sec]	28.38 ± 0.24 [sec]	192
NMF	47.42 ± 66.95 [sec]	28.86 ± 0.43 [sec]	190
iALS	272.61 [sec] / 4.54 ± 5.91 [min]	28.65 ± 0.12 [sec]	191
SpectralCF	2429.47 [sec] / 40.49 ± 24.14 [min]	19.72 ± 0.28 [sec]	279
SpectralCF article default	2111.55 [sec] / 35.19 [min]	20.30 [sec]	270

Table 38. Comparison of the computation time for the different algorithms.

	Movielens 1M ours		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	29.72 [sec]	201
TopPop	0.01 [sec]	32.39 [sec]	184
UserKNN CF cosine	1.67 ± 0.23 [sec]	34.04 ± 0.03 [sec]	175
UserKNN CF dice	1.49 ± 0.21 [sec]	34.04 ± 0.10 [sec]	175
UserKNN CF jaccard	1.50 ± 0.23 [sec]	33.99 ± 0.41 [sec]	175
UserKNN CF asymmetric	1.59 ± 0.19 [sec]	34.16 ± 0.22 [sec]	174
UserKNN CF tversky	1.56 ± 0.21 [sec]	33.95 ± 0.74 [sec]	174
ItemKNN CF cosine	0.45 ± 0.07 [sec]	34.20 ± 0.87 [sec]	173
ItemKNN CF dice	0.46 ± 0.08 [sec]	33.75 ± 0.17 [sec]	176
ItemKNN CF jaccard	0.45 ± 0.07 [sec]	33.90 ± 0.19 [sec]	176
ItemKNN CF asymmetric	0.50 ± 0.07 [sec]	34.32 ± 0.18 [sec]	174
ItemKNN CF tversky	0.43 ± 0.09 [sec]	33.99 ± 0.31 [sec]	176
$P^3\alpha$	2.44 ± 0.93 [sec]	33.77 ± 0.27 [sec]	176
$RP^3\beta$	3.11 ± 1.03 [sec]	32.47 ± 1.99 [sec]	175
$EASE^R$	5.65 ± 0.01 [sec]	33.43 ± 0.31 [sec]	178
SLIM BPR	230.44 [sec] / 3.84 ± 2.74 [min]	34.23 ± 0.10 [sec]	174
SLIMElasticNet	68.77 [sec] / 1.15 ± 0.24 [min]	34.91 ± 0.52 [sec]	169
MF BPR	358.82 [sec] / 5.98 ± 5.73 [min]	33.91 ± 0.41 [sec]	174
MF FunkSVD	328.94 [sec] / 5.48 ± 6.66 [min]	32.76 ± 1.40 [sec]	176
PureSVD	0.32 ± 0.40 [sec]	33.13 ± 0.47 [sec]	178
NMF	28.92 ± 61.24 [sec]	33.66 ± 0.76 [sec]	174
iALS	248.84 [sec] / 4.15 ± 4.96 [min]	33.20 ± 0.64 [sec]	176
SpectralCF	2243.74 [sec] / 37.40 ± 19.07 [min]	21.55 ± 0.33 [sec]	280
SpectralCF article default	2556.16 [sec] / 42.60 [min]	21.74 [sec]	274

G KDD: LEVERAGING META-PATH BASED CONTEXT FOR TOP-N RECOMMENDATION WITH A NEURAL CO-ATTENTION MODEL

Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 39. The results of our evaluation can be seen in Table 40 (Movielens 100k). The corresponding optimal hyperparameters are reported in Table 41 (collaborative KNNs), Table 42 (non-neural machine learning and graph based), Table 43 (content-based KNNs), Table 44 (hybrid KNNs) and Table 45 (MCRec).

Lastly, the time required to train and evaluate the models is reported in Table 46 (Movielens 100k).

Table 39. Dataset characteristics.

Dataset	Interactions	Items	Users	Density
Movielens 100k	100 K	1682	943	6.30%
LastFM	92 K	17 k	1.8 k	0.27%
YelpBusiness	198 K	14 k	16.2 k	0.08%

Table 40. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 100k		
	PREC@10	REC@10	NDCG@10
Random	0.0162	0.0069	0.0084
TopPop	0.1907	0.1180	0.1361
UserKNN CF cosine	0.2807	0.1825	0.2260
UserKNN CF dice	**0.3442**	**0.2237**	**0.2692**
UserKNN CF jaccard	**0.3430**	**0.2225**	**0.2687**
UserKNN CF asymmetric	0.2814	0.1828	0.2264
UserKNN CF tversky	**0.3426**	**0.2227**	**0.2694**
ItemKNN CF cosine	**0.3293**	**0.2152**	**0.2571**
ItemKNN CF dice	**0.3211**	0.2040	0.2425
ItemKNN CF jaccard	**0.3177**	0.2043	0.2431
ItemKNN CF asymmetric	**0.3320**	**0.2171**	**0.2601**
ItemKNN CF tversky	**0.3283**	**0.2145**	**0.2562**
P3alpha	**0.3305**	0.2081	**0.2554**
RP3beta	**0.3435**	**0.2191**	**0.2588**
EASE R	**0.3640**	**0.2318**	**0.2815**
SLIM BPR	**0.3127**	0.2040	0.2460
SLIMElasticNet	**0.3770**	**0.2441**	**0.2957**
MF BPR	0.2816	0.1860	0.2195
MF FunkSVD	**0.3442**	**0.2203**	**0.2642**
PureSVD	**0.3545**	**0.2247**	**0.2719**
NMF	**0.3350**	**0.2139**	**0.2585**
IALS	**0.3596**	**0.2283**	**0.2759**
ItemKNN CBF cosine	0.0455	0.0185	0.0254
ItemKNN CBF dice	0.0135	0.0038	0.0054
ItemKNN CBF jaccard	0.0135	0.0038	0.0054
ItemKNN CBF asymmetric	0.0547	0.0243	0.0319
ItemKNN CBF tversky	0.0097	0.0031	0.0042
ItemKNN CFCBF cosine	**0.3398**	**0.2239**	**0.2646**
ItemKNN CFCBF dice	**0.3215**	0.2043	0.2403
ItemKNN CFCBF jaccard	**0.3200**	0.2057	0.2422
ItemKNN CFCBF asymmetric	**0.3390**	**0.2224**	**0.2662**
ItemKNN CFCBF tversky	**0.3127**	0.2023	0.2439
MCRec	0.3110	0.2113	0.2466

Table 41. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 100k
UserKNN CF cosine	topK	903
	shrink	2
	similarity	cosine
	normalize	True
	feature weighting	BM25
UserKNN CF dice	topK	129
	shrink	0
	similarity	dice
	normalize	True
UserKNN CF jaccard	topK	128
	shrink	0
	similarity	jaccard
	normalize	True
UserKNN CF asymmetric	topK	1000
	shrink	1000
	similarity	asymmetric
	normalize	True
	asymmetric alpha	2.0000
	feature weighting	BM25
UserKNN CF tversky	topK	125
	shrink	28
	similarity	tversky
	normalize	True
	tversky alpha	1.8829
	tversky beta	1.9666
ItemKNN CF cosine	topK	886
	shrink	403
	similarity	cosine
	normalize	True
	feature weighting	BM25
ItemKNN CF dice	topK	179
	shrink	0
	similarity	dice
	normalize	False
ItemKNN CF jaccard	topK	161
	shrink	0
	similarity	jaccard
	normalize	True
ItemKNN CF asymmetric	topK	468
	shrink	706
	similarity	asymmetric
	normalize	True
	asymmetric alpha	1.5629
	feature weighting	BM25
ItemKNN CF tversky	topK	122
	shrink	0
	similarity	tversky
	normalize	True
	tversky alpha	0.8648
	tversky beta	1.5755

Table 42. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Movielens 100k
$P^3\alpha$	topK	197
	alpha	0.0000
	normalize similarity	True
$RP^3\beta$	topK	324
	alpha	0.8593
	beta	0.6574
	normalize similarity	True
$EASE^R$	l2 norm	1.10E+03
SLIM BPR	topK	584
	epochs	120
	symmetric	True
	sgd mode	adam
	lambda i	1.00E-05
	lambda j	1.00E-05
	learning rate	1.00E-01
SLIMElasticNet	topK	605
	l1 ratio	1.13E-04
	alpha	0.2225
MF BPR	sgd mode	adagrad
	epochs	355
	num factors	170
	batch size	256
	positive reg	2.16E-04
	negative reg	4.80E-05
	learning rate	3.97E-02
MF FunkSVD	sgd mode	adagrad
	epochs	135
	use bias	False
	batch size	2
	num factors	16
	item reg	1.00E-02
	user reg	1.00E-02
	learning rate	1.00E-01
	negative quota	0.0782
PureSVD	num factors	13
NMF	num factors	30
	solver	coord. descent
	init type	random
	beta loss	frobenius
iALS	num factors	15
	confidence scaling	log
	alpha	0.0010
	epsilon	0.0010
	reg	2.71E-04
	epochs	10

Table 43. Hyperparameter values for our content based KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 100k
ItemKNN CBF cosine	topK	113
	shrink	349
	similarity	cosine
	normalize	False
	feature weighting	BM25
ItemKNN CBF dice	topK	991
	shrink	1
	similarity	dice
	normalize	True
ItemKNN CBF jaccard	topK	991
	shrink	999
	similarity	jaccard
	normalize	False
ItemKNN CBF asymmetric	topK	403
	shrink	428
	similarity	asymmetric
	normalize	True
	asymmetric alpha	1.8470
	feature weighting	BM25
ItemKNN CBF tversky	topK	983
	shrink	3
	similarity	tversky
	normalize	True
	tversky alpha	0.0501
	tversky beta	0.2996

Table 44. Hyperparameter values for our hybrid KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 100k
ItemKNN CFCBF cosine	topK	355
	shrink	228
	similarity	cosine
	normalize	True
	feature weighting	BM25
	ICM weight	0.0757
ItemKNN CFCBF dice	topK	170
	shrink	0
	similarity	dice
	normalize	True
	ICM weight	0.0100
ItemKNN CFCBF jaccard	topK	164
	shrink	0
	similarity	jaccard
	normalize	True
	ICM weight	100.0000
ItemKNN CFCBF asymmetric	topK	311
	shrink	929
	similarity	asymmetric
	normalize	True
	asymmetric alpha	2.0000
	feature weighting	BM25
	ICM weight	0.0100
ItemKNN CFCBF tversky	topK	70
	shrink	537
	similarity	tversky
	normalize	True
	tversky alpha	0.3134
	tversky beta	1.4108
	ICM weight	0.8798

Table 45. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Movielens 100k
MCRec	epochs	130
	latent dim	128
	reg latent	0.00E+00
	layers	[512, 256, 128, 64]
	reg layes	[0, 0, 0, 0]
	learning rate	1.00E-03
	batch size	256
	num negatives	4

Table 46. Comparison of the computation time for the different algorithms.

	Movielens 100k		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	0.37 [sec]	2513
TopPop	0.00 [sec]	0.41 [sec]	2319
UserKNN CF cosine	0.10 ± 0.02 [sec]	0.86 ± 0.03 [sec]	1077
UserKNN CF dice	0.09 ± 0.02 [sec]	0.75 ± 0.02 [sec]	1283
UserKNN CF jaccard	0.08 ± 0.02 [sec]	0.78 ± 0.05 [sec]	1160
UserKNN CF asymmetric	0.10 ± 0.01 [sec]	0.85 ± 0.03 [sec]	1077
UserKNN CF tversky	0.09 ± 0.02 [sec]	0.76 ± 0.03 [sec]	1256
ItemKNN CF cosine	0.16 ± 0.03 [sec]	0.87 ± 0.02 [sec]	1077
ItemKNN CF dice	0.13 ± 0.03 [sec]	0.80 ± 0.05 [sec]	1256
ItemKNN CF jaccard	0.13 ± 0.03 [sec]	0.75 ± 0.02 [sec]	1256
ItemKNN CF asymmetric	0.15 ± 0.02 [sec]	0.84 ± 0.01 [sec]	1117
ItemKNN CF tversky	0.14 ± 0.04 [sec]	0.76 ± 0.04 [sec]	1256
$P^3\alpha$	0.88 ± 0.50 [sec]	0.73 ± 0.02 [sec]	1256
$RP^3\beta$	0.97 ± 0.50 [sec]	0.77 ± 0.02 [sec]	1231
$EASE^R$	0.57 ± 0.17 [sec]	0.78 ± 0.16 [sec]	1483
SLIM BPR	38.71 ± 16.65 [sec]	1.11 ± 0.04 [sec]	839
SLIMElasticNet	11.45 ± 5.35 [sec]	1.09 ± 0.01 [sec]	862
MF BPR	82.37 [sec] / 1.37 ± 1.20 [min]	1.56 ± 0.22 [sec]	548
MF FunkSVD	148.82 [sec] / 2.48 ± 3.72 [min]	1.69 ± 0.68 [sec]	877
PureSVD	0.05 ± 0.04 [sec]	0.60 ± 0.34 [sec]	1945
NMF	20.65 ± 27.78 [sec]	0.53 [sec]	1774
iALS	26.02 ± 33.39 [sec]	0.75 ± 0.44 [sec]	1774
ItemKNN CBF cosine	0.93 ± 0.61 [sec]	1.06 ± 0.05 [sec]	928
ItemKNN CBF dice	0.92 ± 0.61 [sec]	1.01 ± 0.04 [sec]	900
ItemKNN CBF jaccard	1.02 ± 0.59 [sec]	1.01 ± 0.04 [sec]	914
ItemKNN CBF asymmetric	0.93 ± 0.56 [sec]	1.06 ± 0.01 [sec]	887
ItemKNN CBF tversky	1.18 ± 1.25 [sec]	1.02 ± 0.02 [sec]	914
ItemKNN CFCBF cosine	0.29 ± 0.05 [sec]	1.13 ± 0.02 [sec]	838
ItemKNN CFCBF dice	0.26 ± 0.04 [sec]	1.09 ± 0.04 [sec]	901
ItemKNN CFCBF jaccard	0.26 ± 0.04 [sec]	1.10 ± 0.05 [sec]	900
ItemKNN CFCBF asymmetric	0.28 ± 0.06 [sec]	1.14 ± 0.04 [sec]	838
ItemKNN CFCBF tversky	0.26 ± 0.06 [sec]	1.12 ± 0.08 [sec]	888
MCRec	8496.61 [sec] / 2.36 [hour]	165.63 [sec] / 2.76 [min]	6

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Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 47. The results of our evaluation can be seen in Table 48 (Movielens 1M) and Table 49 (Pinterest). The corresponding optimal hyperparameters are reported in Table 50 (collaborative KNNs), Table 51 (non-neural machine learning and graph based) and Table 52 (NCF).

Lastly, the time required to train and evaluate the models is reported in Table 53 (Movielens 1M) and Table 54 (Pinterest).

Table 47. Dataset characteristics.

Dataset	Interactions	Items	Users	Sparsity
Movielens 1M	1.0 M	3.7 k	6.0 k	95.53%
Pinterest	1.5 M	9.9 k	55.1 k	99.73%

Table 48. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 1M					
	HR@1	NDCG@1	HR@5	NDCG@5	HR@10	NDCG@10
Random	0.0108	0.0108	0.0498	0.0301	0.1033	0.0472
TopPop	0.1051	0.1051	0.3048	0.2064	0.4533	0.2542
UserKNN CF cosine	0.1825	0.1825	0.4925	0.3407	0.6606	0.3951
UserKNN CF dice	0.1911	0.1911	0.5053	0.3522	0.6700	0.4057
UserKNN CF jaccard	0.1906	0.1906	0.5045	0.3521	0.6725	0.4066
UserKNN CF asymmetric	0.1921	0.1921	0.5070	0.3546	0.6768	0.4100
UserKNN CF tversky	0.1921	0.1921	0.5073	0.3536	0.6684	0.4058
ItemKNN CF cosine	0.1825	0.1825	0.4942	0.3414	0.6694	0.3979
ItemKNN CF dice	0.1707	0.1707	0.4856	0.3323	0.6604	0.3887
ItemKNN CF jaccard	0.1692	0.1692	0.4772	0.3268	0.6533	0.3837
ItemKNN CF asymmetric	0.1843	0.1843	0.4906	0.3400	0.6627	0.3956
ItemKNN CF tversky	0.1735	0.1735	0.4856	0.3338	0.6546	0.3884
P3alpha	0.1791	0.1791	0.4846	0.3352	0.6460	0.3876
RP3beta	0.1836	0.1836	0.4935	0.3419	0.6758	0.4011
EASE R	**0.2119**	**0.2119**	**0.5502**	**0.3857**	**0.7098**	**0.4374**
SLIM BPR	0.2013	0.2013	0.5320	0.3713	0.7002	0.4258
SLIMElasticNet	**0.2207**	**0.2207**	**0.5576**	**0.3953**	**0.7162**	**0.4468**
MF BPR	0.1679	0.1679	0.4619	0.3186	0.6305	0.3730
MF FunkSVD	0.2008	0.2008	0.5202	0.3661	0.6844	0.4192
PureSVD	**0.2132**	**0.2132**	0.5339	0.3783	0.6937	0.4303
NMF	0.2056	0.2056	0.5171	0.3651	0.6844	0.4192
IALS	**0.2106**	**0.2106**	**0.5505**	**0.3862**	**0.7109**	**0.4382**
NeuMF	0.2088	0.2088	0.5411	0.3803	0.7093	0.4349

Table 49. Experimental results on the metrics and cutoffs reported in the original paper.

	Pinterest					
	HR@1	NDCG@1	HR@5	NDCG@5	HR@10	NDCG@10
Random	0.0096	0.0096	0.0496	0.0292	0.0997	0.0452
TopPop	0.0467	0.0467	0.1665	0.1064	0.2740	0.1409
UserKNN CF cosine	**0.2892**	**0.2892**	0.7006	**0.5036**	0.8632	0.5566
UserKNN CF dice	**0.2880**	**0.2880**	0.7039	**0.5047**	0.8649	0.5572
UserKNN CF jaccard	**0.2898**	**0.2898**	0.7038	**0.5056**	0.8655	**0.5583**
UserKNN CF asymmetric	**0.2877**	**0.2877**	0.7040	**0.5046**	0.8655	0.5573
UserKNN CF tversky	**0.2889**	**0.2889**	0.7039	**0.5052**	0.8660	**0.5580**
ItemKNN CF cosine	**0.2900**	**0.2900**	**0.7109**	**0.5090**	0.8762	**0.5628**
ItemKNN CF dice	**0.2917**	**0.2917**	0.7098	**0.5092**	0.8765	**0.5635**
ItemKNN CF jaccard	**0.2910**	**0.2910**	0.7093	**0.5086**	0.8763	**0.5631**
ItemKNN CF asymmetric	**0.2903**	**0.2903**	**0.7117**	**0.5096**	0.8766	**0.5633**
ItemKNN CF tversky	**0.2909**	**0.2909**	0.7093	**0.5086**	0.8760	**0.5629**
P3alpha	**0.2853**	**0.2853**	0.7022	0.5024	0.8700	0.5571
RP3beta	**0.2966**	**0.2966**	**0.7151**	**0.5149**	**0.8796**	**0.5685**
EASE R	**0.2889**	**0.2889**	0.7053	**0.5057**	0.8682	**0.5589**
SLIM BPR	**0.2983**	**0.2983**	**0.7117**	**0.5138**	0.8736	**0.5666**
SLIMElasticNet	**0.2913**	**0.2913**	0.7059	**0.5072**	0.8679	**0.5601**
MF BPR	0.2655	0.2655	0.6858	0.4833	0.8651	0.5418
MF FunkSVD	0.2601	0.2601	0.6890	0.4820	0.8658	0.5398
PureSVD	0.2630	0.2630	0.6628	0.4706	0.8268	0.5241
NMF	0.2307	0.2307	0.6445	0.4434	0.8343	0.5052
IALS	**0.2811**	**0.2811**	**0.7144**	**0.5061**	0.8761	**0.5590**
NeuMF	0.2801	0.2801	0.7101	0.5029	0.8777	0.5576

Table 50. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Pinterest
UserKNN CF cosine	normalize	True	True
	topK	516	1000
	feature weighting	BM25	BM25
	similarity	cosine	cosine
	shrink	0	0
UserKNN CF dice	normalize	True	True
	topK	246	991
	similarity	dice	dice
	shrink	0	138
UserKNN CF jaccard	normalize	True	True
	topK	259	972
	similarity	jaccard	jaccard
	shrink	0	0
UserKNN CF asymmetric	topK	306	1000
	feature weighting	TF-IDF	TF-IDF
	asymmetric alpha	0.2173	0.0000
	normalize	True	True
	similarity	asymmetric	asymmetric
	shrink	0	1000
UserKNN CF tversky	normalize	True	True
	topK	267	1000
	tversky alpha	0.6394	2.0000
	tversky beta	0.8051	1.9574
	similarity	tversky	tversky
	shrink	0	33
ItemKNN CF cosine	normalize	True	False
	topK	111	1000
	feature weighting	BM25	BM25
	similarity	cosine	cosine
	shrink	298	4
ItemKNN CF dice	normalize	True	True
	topK	61	1000
	similarity	dice	dice
	shrink	0	0
ItemKNN CF jaccard	normalize	False	False
	topK	62	997
	similarity	jaccard	jaccard
	shrink	19	1
ItemKNN CF asymmetric	topK	206	1000
	feature weighting	BM25	BM25
	asymmetric alpha	0.6914	0.0000
	normalize	True	True
	similarity	asymmetric	asymmetric
	shrink	1000	1000
ItemKNN CF tversky	normalize	True	True
	topK	83	1000
	tversky alpha	0.0000	2.0000
	tversky beta	2.0000	2.0000
	similarity	tversky	tversky
	shrink	561	0

Table 51. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Pinterest
$RP^3\beta$	alpha	1.0807	0.8616
	topK	546	1000
	normalize similarity	True	True
	beta	0.7029	0.4255
$EASE^R$	l2 norm	2.96E+03	-
SLIM BPR	learning rate	3.08E-02	1.00E-01
	sgd mode	adagrad	adagrad
	symmetric	True	True
	epochs	285	180
	lambda i	1.00E-02	1.00E-02
	topK	1000	916
	lambda j	4.51E-03	3.83E-05
SLIMElasticNet	l1 ratio	1.19E-05	1.15E-04
	alpha	0.0788	0.0526
	topK	544	1000
MF BPR	positive reg	2.08E-05	1.00E-02
	num factors	200	200
	negative reg	1.00E-02	6.59E-03
	epochs	625	615
	batch size	8	2
	sgd mode	adagrad	adagrad
	learning rate	5.88E-02	6.74E-02
MF FunkSVD	sgd mode	adam	adagrad
	num factors	50	28
	negative quota	0.1651	0.4052
	user reg	7.35E-04	6.49E-04
	learning rate	4.38E-04	3.17E-02
	epochs	160	305
	batch size	512	1
	item reg	4.83E-03	1.56E-03
	use bias	True	True
PureSVD	num factors	52	50
NMF	init type	random	nndsvda
	beta loss	frobenius	kullback-leibler
	num factors	89	27
	solver	mult. update	mult. update
iALS	num factors	46	30
	epochs	10	45
	epsilon	10.0000	0.0010
	confidence scaling	log	linear
	reg	1.00E-05	1.00E-02
	alpha	50.0000	50.0000

Table 52. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Pinterest
NeuMF	epochs	10	5
	epochs gmf	10	45
	epochs mlp	10	10
	batch size	256	256
	num factors	64	16
	layers	[256, 128, 64]	[64, 32, 16]
	reg mf	0.00E+00	0.00E+00
	reg layers	[0, 0, 0]	[0, 0, 0]
	num negatives	4	4
	learning rate	1.00E-03	1.00E-03
	learning rate pretrain	1.00E-03	1.00E-03
	learner	sgd	sgd
	learner pretrain	adam	adam
	pretrain	True	True

Table 53. Comparison of the computation time for the different algorithms.

	Movielens 1M		
	Train time	Recommendation Time	[usr/s]
Random	0.04 [sec]	36.31 [sec]	166
TopPop	0.06 [sec]	37.88 [sec]	159
UserKNN CF cosine	9.01 ± 0.26 [sec]	48.07 ± 1.08 [sec]	126
UserKNN CF dice	9.00 ± 0.31 [sec]	47.37 ± 1.63 [sec]	130
UserKNN CF jaccard	8.98 ± 0.29 [sec]	46.70 ± 1.38 [sec]	130
UserKNN CF asymmetric	9.06 ± 0.30 [sec]	47.01 ± 1.83 [sec]	129
UserKNN CF tversky	9.09 ± 0.39 [sec]	46.66 ± 2.00 [sec]	130
ItemKNN CF cosine	4.04 ± 0.17 [sec]	49.48 ± 4.20 [sec]	130
ItemKNN CF dice	4.07 ± 0.17 [sec]	47.25 ± 2.28 [sec]	133
ItemKNN CF jaccard	4.09 ± 0.19 [sec]	47.56 ± 3.43 [sec]	134
ItemKNN CF asymmetric	4.10 ± 0.15 [sec]	50.21 ± 1.92 [sec]	127
ItemKNN CF tversky	4.09 ± 0.18 [sec]	45.82 ± 1.18 [sec]	133
$P^3\alpha$	7.61 ± 2.17 [sec]	45.84 ± 0.56 [sec]	131
$RP^3\beta$	8.05 ± 2.55 [sec]	46.76 ± 0.42 [sec]	127
$EASE^R$	12.34 ± 0.03 [sec]	46.25 ± 0.47 [sec]	130
SLIM BPR	785.57 [sec] / 13.09 ± 7.36 [min]	49.96 ± 2.04 [sec]	118
SLIMElasticNet	252.72 [sec] / 4.21 ± 2.51 [min]	46.78 ± 0.22 [sec]	129
MF BPR	937.36 [sec] / 15.62 ± 12.59 [min]	56.94 ± 9.66 [sec]	98
MF FunkSVD	3594.07 [sec] / 59.90 ± 47.65 [min]	41.99 ± 7.61 [sec]	154
PureSVD	2.84 ± 1.96 [sec]	44.36 ± 10.92 [sec]	153
NMF	721.37 [sec] / 12.02 ± 22.88 [min]	55.73 ± 12.22 [sec]	151
iALS	1022.66 [sec] / 17.04 ± 13.53 [min]	42.97 ± 8.91 [sec]	154
NeuMF	15050.89 [sec] / 4.18 [hour]	293.85 [sec] / 4.90 [min]	21

Table 54. Comparison of the computation time for the different algorithms.

	Pinterest		
	Train time	Recommendation Time	[usr/s]
Random	0.04 [sec]	337.91 [sec] / 5.63 [min]	163
TopPop	0.08 [sec]	350.44 [sec] / 5.84 [min]	157
UserKNN CF cosine	59.52 ± 3.87 [sec]	442.63 [sec] / 7.38 ± 0.11 [min]	122
UserKNN CF dice	60.07 [sec] / 1.00 ± 0.05 [min]	440.65 [sec] / 7.34 ± 0.10 [min]	124
UserKNN CF jaccard	59.33 ± 3.16 [sec]	443.67 [sec] / 7.39 ± 0.05 [min]	124
UserKNN CF asymmetric	60.80 [sec] / 1.01 ± 0.04 [min]	445.33 [sec] / 7.42 ± 0.01 [min]	124
UserKNN CF tversky	60.89 [sec] / 1.01 ± 0.06 [min]	435.42 [sec] / 7.26 ± 0.23 [min]	124
ItemKNN CF cosine	3.73 ± 0.40 [sec]	435.26 [sec] / 7.25 ± 0.04 [min]	126
ItemKNN CF dice	3.56 ± 0.37 [sec]	433.80 [sec] / 7.23 ± 0.05 [min]	126
ItemKNN CF jaccard	3.70 ± 0.36 [sec]	435.32 [sec] / 7.26 ± 0.05 [min]	126
ItemKNN CF asymmetric	3.69 ± 0.35 [sec]	437.39 [sec] / 7.29 ± 0.05 [min]	126
ItemKNN CF tversky	3.64 ± 0.40 [sec]	436.99 [sec] / 7.28 ± 0.04 [min]	126
$P^3\alpha$	17.69 ± 4.33 [sec]	434.43 [sec] / 7.24 ± 0.02 [min]	127
$RP^3\beta$	17.95 ± 4.99 [sec]	433.36 [sec] / 7.22 ± 0.06 [min]	126
$EASE^R$	123.69 [sec] / 2.06 ± 0.00 [min]	409.54 [sec] / 6.83 ± 0.02 [min]	135
SLIM BPR	4566.45 [sec] / 1.27 ± 0.55 [hour]	434.78 [sec] / 7.25 ± 0.05 [min]	127
SLIMElasticNet	728.11 [sec] / 12.14 ± 5.73 [min]	428.35 [sec] / 7.14 ± 0.23 [min]	125
MF BPR	12620.32 [sec] / 3.51 ± 2.83 [hour]	461.88 [sec] / 7.70 ± 1.94 [min]	95
MF FunkSVD	8736.15 [sec] / 2.43 ± 1.89 [hour]	443.13 [sec] / 7.39 ± 1.77 [min]	150
PureSVD	6.58 ± 5.41 [sec]	430.77 [sec] / 7.18 ± 1.83 [min]	149
NMF	963.74 [sec] / 16.06 ± 22.37 [min]	543.13 [sec] / 9.05 ± 1.92 [min]	149
iALS	10812.68 [sec] / 3.00 ± 3.91 [hour]	372.05 [sec] / 6.20 ± 0.03 [min]	148
NeuMF	167670.36 [sec] / 1.94 [day]	6995.33 [sec] / 1.94 [hour]	8

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Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 55. The results of our evaluation can be seen in Table 56 (Movielens 20M) and Table 57 (Netflix Prize). The corresponding optimal hyperparameters are reported in Table 58 (collaborative KNNs), Table 59 (non-neural machine learning and graph based) and Table 60 (Mult VAE).

Lastly, the time required to train and evaluate the models is reported in Table 61 (Movielens 20M) and Table 62 (Netflix Prize).

Table 55. Dataset characteristics.

Dataset	Interactions	Users	Items	Density	Held out users
Movielens 20M	10.0M	136k	20k	0.36	10k
Netflix Prize	56.9M	463k	17k	0.69	40k

Table 56. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 20M					
	REC@20	NDCG@20	REC@50	NDCG@50	REC@100	NDCG@100
Random	0.0008	0.0006	0.0025	0.0013	0.0053	0.0022
TopPop	0.1441	0.1201	0.2320	0.1569	0.3296	0.1901
ItemKNN CF cosine	0.2897	0.2434	0.4412	0.3054	0.5652	0.3492
ItemKNN CF dice	0.2689	0.2274	0.4095	0.2851	0.5316	0.3277
ItemKNN CF jaccard	0.2667	0.2284	0.4035	0.2844	0.5254	0.3268
ItemKNN CF asymmetric	0.2937	0.2444	0.4486	0.3087	0.5709	0.3527
ItemKNN CF tversky	0.2867	0.2395	0.4393	0.3030	0.5556	0.3458
$P^3\alpha$	0.2620	0.2168	0.4047	0.2742	0.5287	0.3182
$RP^3\beta$	0.3006	0.2501	0.4540	0.3133	0.5797	0.3583
$EASE^R$	0.3100	0.2639	0.4608	0.3267	0.5860	0.3711
SLIM BPR	0.3206	0.2646	0.4783	0.3291	0.6030	0.3731
SLIMElasticNet	0.3356	0.2920	0.4893	0.3576	0.6110	0.4017
PureSVD	0.1620	0.1137	0.2778	0.1593	0.3974	0.1995
iALS	0.2030	0.1340	0.3628	0.1954	0.4976	0.2418
Mult VAE	**0.3541**	**0.2988**	**0.5222**	**0.3690**	**0.6517**	**0.4158**

Table 57. Experimental results on the metrics and cutoffs reported in the original paper.

	Netflix Prize					
	REC@20	NDCG@20	REC@50	NDCG@50	REC@100	NDCG@100
Random	0.0011	0.0010	0.0027	0.0018	0.0054	0.0030
TopPop	0.0786	0.0762	0.1643	0.1159	0.2717	0.1570
ItemKNN CF cosine	0.2091	0.1970	0.3387	0.2592	0.4598	0.3092
ItemKNN CF dice	0.1963	0.1862	0.3224	0.2479	0.4379	0.2983
ItemKNN CF jaccard	0.1997	0.1883	0.3248	0.2481	0.4450	0.2978
ItemKNN CF asymmetric	0.2119	0.1968	0.3466	0.2623	0.4764	0.3165
ItemKNN CF tversky	0.2075	0.1933	0.3420	0.2582	0.4708	0.3118
$P^3\alpha$	0.1960	0.1759	0.3325	0.2412	0.4633	0.2962
$RP^3\beta$	0.2210	0.2053	0.3633	0.2739	0.4932	0.3281
$EASE^R$	0.2393	0.2288	0.3801	0.2978	0.5072	0.3510
SLIM BPR	0.2394	0.2219	0.3767	0.2886	0.5004	0.3403
SLIMElasticNet	0.2555	**0.2479**	0.4002	**0.3203**	0.5299	**0.3752**
PureSVD	0.1177	0.0908	0.2193	0.1357	0.3247	0.1765
iALS	0.1397	0.1014	0.2675	0.1570	0.3930	0.2066
Mult VAE	**0.2615**	0.2423	**0.4127**	0.3167	**0.5456**	0.3730

Table 58. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 20M	Netflix Prize
ItemKNN CF cosine	topK	278	140
	shrink	409	1000
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	BM25	BM25
ItemKNN CF dice	topK	107	9
	shrink	3	983
	similarity	dice	dice
	normalize	True	True
ItemKNN CF jaccard	topK	118	54
	shrink	214	544
	similarity	jaccard	jaccard
	normalize	True	True
ItemKNN CF asymmetric	topK	52	64
	shrink	0	360
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.9034	0.2002
	feature weighting	BM25	none
ItemKNN CF tversky	topK	25	54
	shrink	273	1000
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.0782	0.1997
	tversky beta	0.5191	0.9652

Table 59. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Movielens 20M	Netflix Prize
$P^3\alpha$	topK	523	534
	alpha	0.5575	1.6695
	normalize similarity	True	True
$RP^3\beta$	topK	399	185
	alpha	0.7242	1.3871
	beta	0.4945	0.4271
	normalize similarity	True	True
$EASE^R$	l2 norm	3.99E+04	1.12E+05
SLIM BPR	topK	847	491
	epochs	630	240
	symmetric	True	True
	sgd mode	sgd	sgd
	lambda i	5.69E-05	5.87E-04
	lambda j	1.00E-05	1.00E-02
	learning rate	4.56E-03	7.53E-03
SLIMElasticNet	topK	718	1000
	l1 ratio	6.74E-03	9.65E-04
	alpha	0.0010	0.0010
PureSVD	num factors	25	51
	estimate model for cold users	itemKNN	itemKNN
iALS	num factors	54	78
	confidence scaling	linear	log
	alpha	11.0139	50.0000
	epsilon	10.0000	10.0000
	reg	1.00E-02	1.00E-05
	estimate model for cold users	itemKNN	itemKNN

Table 60. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Movielens 20M	Netflix Prize
Mult VAE	epochs	95	80
	batch size	500	500
	total anneal steps	200000	200000
	p dims	-	-

Table 61. Comparison of the computation time for the different algorithms.

	Movielens 20M		
	Train time	Recommendation Time	[usr/s]
Random	0.23 [sec]	13.64 [sec]	733
TopPop	0.38 [sec]	12.62 [sec]	792
UserKNN CF cosine	-	-	-
UserKNN CF dice	-	-	-
UserKNN CF jaccard	-	-	-
UserKNN CF asymmetric	-	-	-
UserKNN CF tversky	-	-	-
ItemKNN CF cosine	12.12 ± 0.53 [sec]	17.66 ± 2.93 [sec]	651
ItemKNN CF dice	11.85 ± 0.45 [sec]	13.84 ± 0.69 [sec]	741
ItemKNN CF jaccard	11.74 ± 0.46 [sec]	14.08 ± 0.67 [sec]	723
ItemKNN CF asymmetric	12.29 ± 0.71 [sec]	15.81 ± 1.82 [sec]	736
ItemKNN CF tversky	11.79 ± 0.58 [sec]	15.24 ± 2.53 [sec]	764
$P^3\alpha$	24.76 ± 4.74 [sec]	12.61 ± 0.31 [sec]	822
$RP^3\beta$	25.39 ± 5.11 [sec]	13.09 ± 0.68 [sec]	767
$EASE^R$	195.45 [sec] / 3.26 ± 0.09 [min]	17.86 ± 0.96 [sec]	561
SLIM BPR	2315.60 [sec] / 38.59 ± 48.48 [min]	13.97 ± 1.00 [sec]	690
SLIMElasticNet	6508.83 [sec] / 1.81 ± 1.26 [hour]	13.88 ± 0.70 [sec]	708
PureSVD	10.78 ± 9.06 [sec]	33.89 ± 10.20 [sec]	260
iALS	1352.64 [sec] / 22.54 ± 19.35 [min]	34.69 ± 8.11 [sec]	279
Mult VAE	1296.97 [sec] / 21.62 [min]	18.72 [sec]	534

Table 62. Comparison of the computation time for the different algorithms.

	Netflix Prize		
	Train time	Recommendation Time	[usr/s]
Random	1.67 [sec]	60.99 [sec] / 1.02 [min]	656
TopPop	2.95 [sec]	59.14 [sec]	676
UserKNN CF cosine	-	-	-
UserKNN CF dice	-	-	-
UserKNN CF jaccard	-	-	-
UserKNN CF asymmetric	-	-	-
UserKNN CF tversky	-	-	-
ItemKNN CF cosine	65.70 [sec] / 1.09 ± 0.03 [min]	84.91 [sec] / 1.42 ± 0.46 [min]	593
ItemKNN CF dice	64.29 [sec] / 1.07 ± 0.01 [min]	63.77 [sec] / 1.06 ± 0.08 [min]	682
ItemKNN CF jaccard	64.40 [sec] / 1.07 ± 0.01 [min]	61.38 [sec] / 1.02 [min]	652
ItemKNN CF asymmetric	65.41 [sec] / 1.09 ± 0.04 [min]	97.70 [sec] / 1.63 ± 0.59 [min]	654
ItemKNN CF tversky	64.82 [sec] / 1.08 ± 0.01 [min]	66.06 [sec] / 1.10 ± 0.12 [min]	657
$P^3\alpha$	74.12 [sec] / 1.24 ± 0.08 [min]	59.98 ± 0.57 [sec]	666
$RP^3\beta$	75.10 [sec] / 1.25 ± 0.09 [min]	58.00 ± 5.61 [sec]	648
$EASE^R$	205.33 [sec] / 3.42 ± 0.04 [min]	85.09 [sec] / 1.42 ± 0.01 [min]	473
SLIM BPR	5741.37 [sec] / 1.59 ± 1.80 [hour]	65.49 [sec] / 1.09 ± 0.09 [min]	600
SLIMElasticNet	29589.53 [sec] / 8.22 ± 7.70 [hour]	69.53 [sec] / 1.16 ± 0.13 [min]	580
PureSVD	85.66 [sec] / 1.43 ± 0.92 [min]	156.60 [sec] / 2.61 ± 0.33 [min]	245
iALS	6101.72 [sec] / 1.69 ± 1.16 [hour]	153.64 [sec] / 2.56 ± 0.12 [min]	265
Mult VAE	4521.33 [sec] / 1.26 [hour]	81.53 [sec] / 1.36 [min]	491

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Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 63. The results of our evaluation can be seen in Table 64 (Gowalla) and Table 65 (Yelp). The corresponding optimal hyperparameters are reported in Table 66 (collaborative KNNs), Table 67 (non-neural machine learning and graph based) and Table 68 (ConvNCF).

Lastly, the time required to train and evaluate the models is reported in Table 69 (Gowalla) and Table 70 (Yelp).

Table 63. Dataset characteristics.

Dataset	Interactions	Items	Users	Density
Yelp	69K	25815	25677	0.105
Gowalla	1249K	52400	54156	0.044

Table 64. Experimental results on the metrics and cutoffs reported in the original paper.

	Gowalla					
	HR@5	NDCG@5	HR@10	NDCG@10	HR@20	NDCG@20
Random	0.0049	0.0029	0.0099	0.0045	0.0205	0.0071
TopPop	0.2188	0.1652	0.2910	0.1884	0.3803	0.2110
UserKNN CF cosine	**0.7131**	**0.5879**	**0.7939**	**0.6142**	0.8532	**0.6293**
UserKNN CF dice	**0.6848**	**0.5632**	0.7649	**0.5893**	0.8226	**0.6039**
UserKNN CF jaccard	**0.6786**	**0.5572**	0.7597	**0.5836**	0.8174	**0.5983**
UserKNN CF asymmetric	**0.6720**	**0.5486**	0.7555	**0.5758**	0.8156	**0.5911**
UserKNN CF tversky	**0.6769**	**0.5556**	0.7579	**0.5820**	0.8149	**0.5965**
ItemKNN CF cosine	**0.6806**	**0.5511**	0.7668	**0.5792**	0.8257	**0.5942**
ItemKNN CF dice	0.6605	0.5231	0.7592	0.5552	0.8280	0.5728
ItemKNN CF jaccard	**0.6890**	**0.5577**	0.7752	**0.5857**	0.8306	**0.5999**
ItemKNN CF asymmetric	**0.6953**	**0.5711**	0.7762	**0.5974**	0.8332	**0.6119**
ItemKNN CF tversky	**0.7047**	**0.5864**	0.7790	**0.6105**	0.8331	**0.6244**
P3alpha	**0.6926**	**0.5703**	0.7674	**0.5948**	0.8158	**0.6071**
RP3beta	**0.6836**	**0.5525**	0.7723	**0.5814**	0.8361	**0.5976**
EASE R	-	-	-	-	-	-
SLIM BPR	-	-	-	-	-	-
SLIMElasticNet	0.6365	**0.5284**	0.7083	0.5517	0.7608	0.5651
MF BPR	0.6376	0.4996	0.7416	0.5334	0.8234	0.5542
MF FunkSVD	0.6029	0.4592	0.7216	0.4979	0.8082	0.5199
PureSVD	0.5653	0.4482	0.6627	0.4798	0.7393	0.4993
NMF	0.5856	0.4607	0.6842	0.4927	0.7674	0.5138
IALS	0.6460	0.5081	0.7554	0.5436	0.8356	0.5641
ConvNCF	0.6702	0.5233	0.7799	0.5590	**0.8623**	0.5799

Table 65. Experimental results on the metrics and cutoffs reported in the original paper.

	Yelp					
	HR@5	NDCG@5	HR@10	NDCG@10	HR@20	NDCG@20
Random	0.0055	0.0032	0.0103	0.0048	0.0199	0.0072
TopPop	0.0817	0.0538	0.1200	0.0661	0.1751	0.0799
UserKNN CF cosine	**0.2068**	**0.1355**	**0.3126**	**0.1695**	0.4401	**0.2017**
UserKNN CF dice	**0.1994**	**0.1306**	0.3013	**0.1634**	0.4271	0.1951
UserKNN CF jaccard	**0.2006**	**0.1311**	0.3023	**0.1638**	0.4286	0.1956
UserKNN CF asymmetric	**0.2131**	**0.1400**	**0.3209**	**0.1747**	**0.4482**	**0.2068**
UserKNN CF tversky	**0.2046**	**0.1347**	0.3049	**0.1670**	0.4320	**0.1990**
ItemKNN CF cosine	**0.2521**	**0.1686**	**0.3669**	**0.2056**	**0.4974**	**0.2385**
ItemKNN CF dice	**0.2329**	**0.1564**	**0.3395**	**0.1908**	**0.4664**	**0.2228**
ItemKNN CF jaccard	**0.2414**	**0.1634**	**0.3512**	**0.1988**	**0.4786**	**0.2309**
ItemKNN CF asymmetric	**0.2421**	**0.1598**	**0.3514**	**0.1950**	**0.4815**	**0.2278**
ItemKNN CF tversky	**0.2303**	**0.1546**	**0.3346**	**0.1884**	**0.4563**	**0.2192**
P3alpha	**0.2146**	**0.1395**	**0.3211**	**0.1737**	0.4442	**0.2049**
RP3beta	**0.2202**	**0.1431**	**0.3323**	**0.1793**	**0.4667**	**0.2132**
EASE R	-	-	-	-	-	-
SLIM BPR	-	-	-	-	-	-
SLIMElasticNet	**0.2330**	**0.1535**	**0.3475**	**0.1904**	**0.4799**	**0.2238**
MF BPR	0.1557	0.1024	0.2421	0.1302	0.3599	0.1598
MF FunkSVD	0.1728	0.1121	0.2621	0.1409	0.3727	0.1688
PureSVD	**0.2011**	**0.1307**	0.3002	**0.1626**	0.4238	0.1938
NMF	0.1817	0.1172	0.2824	0.1496	0.4090	0.1815
IALS	**0.2048**	**0.1348**	**0.3080**	**0.1680**	0.4319	**0.1993**
ConvNCF	0.1947	0.1250	0.3059	0.1608	0.4446	0.1957

Table 66. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Yelp	Gowalla
UserKNN CF cosine	topK	470	1000
	shrink	0	1000
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	none	TF-IDF
UserKNN CF dice	topK	494	513
	shrink	0	10
	similarity	dice	dice
	normalize	False	True
UserKNN CF jaccard	topK	553	455
	shrink	2	5
	similarity	jaccard	jaccard
	normalize	False	True
UserKNN CF asymmetric	topK	529	451
	shrink	721	173
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.1781	0.6950
	feature weighting	TF-IDF	TF-IDF
UserKNN CF tversky	topK	474	368
	shrink	67	0
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	1.9756	1.3012
	tversky beta	1.9345	2.0000
ItemKNN CF cosine	topK	1000	317
	shrink	387	1000
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	TF-IDF	TF-IDF
ItemKNN CF dice	topK	195	409
	shrink	10	20
	similarity	dice	dice
	normalize	False	True
ItemKNN CF jaccard	topK	479	302
	shrink	4	68
	similarity	jaccard	jaccard
	normalize	True	True
ItemKNN CF asymmetric	topK	918	712
	shrink	154	507
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.3530	0.2575
	feature weighting	TF-IDF	TF-IDF
ItemKNN CF tversky	topK	374	944
	shrink	0	16
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.7020	0.0558
	tversky beta	1.5460	1.9805

Table 67. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Yelp	Gowalla
$P^3\alpha$	topK	584	413
	alpha	0.3672	0.4424
	normalize similarity	True	True
$RP^3\beta$	topK	1000	640
	alpha	0.5548	0.5168
	beta	0.3389	0.2009
	normalize similarity	False	True
$EASE^R$	l2 norm	-	-
SLIM BPR	topK	-	795
	epochs	-	570
	symmetric	-	False
	sgd mode	-	adagrad
	lambda i	-	4.42E-04
	lambda j	-	2.16E-04
	learning rate	-	2.98E-03
SLIMElasticNet	topK	1000	916
	l1 ratio	2.66E-05	4.30E-04
	alpha	0.0520	0.0010
MF BPR	sgd mode	adam	adam
	epochs	1420	1485
	num factors	200	200
	batch size	32	16
	positive reg	1.00E-02	1.00E-02
	negative reg	1.00E-02	1.00E-02
	learning rate	5.70E-04	1.69E-03
MF FunkSVD	sgd mode	adam	adam
	epochs	365	410
	use bias	True	True
	batch size	32	4
	num factors	103	192
	item reg	1.43E-05	1.02E-04
	user reg	9.96E-03	2.88E-04
	learning rate	2.16E-03	1.41E-03
	negative quota	0.0642	0.1492
PureSVD	num factors	70	350
NMF	num factors	53	286
	solver	mult. update	mult. update
	init type	random	nndsvda
	beta loss	kullback-leibler	kullback-leibler
iALS	num factors	145	200
	confidence scaling	log	log
	alpha	7.3331	50.0000
	epsilon	0.0270	0.1846
	reg	4.50E-03	1.00E-02
	epochs	60	5

Table 68. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Yelp	Gowalla
ConvNCF	batch size	512	512
	epochs	145	445
	epochs MFBPR	480	490
	embedding size	64	64
	hidden size	128	128
	negative sample per positive	1	1
	negative instances per positive	4	4
	regularization users items	1.00E-02	1.00E-02
	regularization weights	1.00E+01	1.00E+01
	regularization filter weights	1.00E+00	1.00E+00
	learning rate embeddings	5.00E-02	5.00E-02
	learning rate CNN	5.00E-02	5.00E-02
	channel size	[32, 32, 32, 32, 32, 32]	[32, 32, 32, 32, 32, 32]
	dropout	0.0000	0.0000

Table 69. Comparison of the computation time for the different algorithms.

	Gowalla		
	Train time	Recommendation Time	[usr/s]
Random	0.04 [sec]	94.26 [sec] / 1.57 [min]	575
TopPop	0.08 [sec]	112.67 [sec] / 1.88 [min]	481
UserKNN CF cosine	24.25 ± 1.03 [sec]	161.09 [sec] / 2.68 ± 0.07 [min]	322
UserKNN CF dice	25.07 ± 0.93 [sec]	161.77 [sec] / 2.70 ± 0.03 [min]	332
UserKNN CF jaccard	25.07 ± 0.88 [sec]	161.03 [sec] / 2.68 ± 0.08 [min]	334
UserKNN CF asymmetric	25.75 ± 1.03 [sec]	161.07 [sec] / 2.68 ± 0.09 [min]	334
UserKNN CF tversky	25.62 ± 0.92 [sec]	162.28 [sec] / 2.70 ± 0.03 [min]	337
ItemKNN CF cosine	25.63 ± 1.65 [sec]	162.49 [sec] / 2.71 ± 0.03 [min]	338
ItemKNN CF dice	24.78 ± 1.52 [sec]	166.14 [sec] / 2.77 ± 0.09 [min]	339
ItemKNN CF jaccard	24.87 ± 1.55 [sec]	163.76 [sec] / 2.73 ± 0.07 [min]	341
ItemKNN CF asymmetric	25.52 ± 1.85 [sec]	166.42 [sec] / 2.77 ± 0.08 [min]	329
ItemKNN CF tversky	25.92 ± 1.72 [sec]	164.91 [sec] / 2.75 ± 0.07 [min]	324
$P^3\alpha$	90.96 [sec] / 1.52 ± 0.27 [min]	156.74 [sec] / 2.61 ± 0.04 [min]	348
$RP^3\beta$	103.55 [sec] / 1.73 ± 0.31 [min]	159.29 [sec] / 2.65 ± 0.01 [min]	342
$EASE^R$	-	-	-
SLIM BPR	24663.44 [sec] / 6.85 ± 4.36 [hour]	165.90 [sec] / 2.76 ± 0.11 [min]	316
SLIMElasticNet	4531.84 [sec] / 1.26 ± 0.70 [hour]	158.98 [sec] / 2.65 ± 0.17 [min]	329
MF BPR	19828.95 [sec] / 5.51 ± 2.32 [hour]	128.32 [sec] / 2.14 ± 0.09 [min]	413
MF FunkSVD	14731.56 [sec] / 4.09 ± 2.15 [hour]	136.27 [sec] / 2.27 ± 0.13 [min]	383
PureSVD	11.12 ± 3.45 [sec]	321.24 [sec] / 5.35 ± 0.60 [min]	159
NMF	2368.87 [sec] / 39.48 ± 23.03 [min]	251.74 [sec] / 4.20 ± 0.68 [min]	195
iALS	2695.70 [sec] / 44.93 ± 26.66 [min]	129.40 [sec] / 2.16 ± 0.05 [min]	413
ConvNCF	44743.03 [sec] / 12.43 [hour]	233.89 [sec] / 3.90 [min]	232

Table 70. Comparison of the computation time for the different algorithms.

	Yelp		
	Train time	Recommendation Time	[usr/s]
Random	0.02 [sec]	44.30 [sec]	580
TopPop	0.03 [sec]	49.17 [sec]	522
UserKNN CF cosine	8.93 ± 0.65 [sec]	74.11 [sec] / 1.24 ± 0.01 [min]	348
UserKNN CF dice	9.26 ± 0.72 [sec]	74.30 [sec] / 1.24 ± 0.01 [min]	347
UserKNN CF jaccard	9.18 ± 0.69 [sec]	73.27 [sec] / 1.22 ± 0.01 [min]	348
UserKNN CF asymmetric	9.21 ± 0.96 [sec]	74.33 [sec] / 1.24 ± 0.02 [min]	346
UserKNN CF tversky	9.43 ± 0.70 [sec]	74.67 [sec] / 1.24 ± 0.02 [min]	350
ItemKNN CF cosine	8.04 ± 0.88 [sec]	75.74 [sec] / 1.26 ± 0.04 [min]	328
ItemKNN CF dice	7.95 ± 0.70 [sec]	73.03 [sec] / 1.22 ± 0.04 [min]	361
ItemKNN CF jaccard	7.95 ± 0.74 [sec]	74.48 [sec] / 1.24 ± 0.04 [min]	347
ItemKNN CF asymmetric	8.46 ± 0.79 [sec]	77.62 [sec] / 1.29 ± 0.02 [min]	336
ItemKNN CF tversky	8.13 ± 0.70 [sec]	73.72 [sec] / 1.23 ± 0.03 [min]	355
$P^3\alpha$	33.85 ± 5.97 [sec]	71.02 [sec] / 1.18 ± 0.01 [min]	363
$RP^3\beta$	37.25 ± 9.81 [sec]	71.48 [sec] / 1.19 ± 0.04 [min]	349
$EASE^R$	-	-	-
SLIM BPR	-	-	-
SLIMElasticNet	846.95 [sec] / 14.12 ± 6.92 [min]	68.16 [sec] / 1.14 ± 0.07 [min]	361
MF BPR	3981.91 [sec] / 1.11 ± 0.88 [hour]	50.36 ± 1.71 [sec]	495
MF FunkSVD	3944.58 [sec] / 1.10 ± 0.85 [hour]	51.88 ± 1.46 [sec]	501
PureSVD	2.35 ± 1.79 [sec]	56.89 ± 4.49 [sec]	466
NMF	952.10 [sec] / 15.87 ± 6.43 [min]	75.16 [sec] / 1.25 ± 0.47 [min]	464
iALS	1778.07 [sec] / 29.63 ± 19.78 [min]	47.35 ± 1.33 [sec]	530
ConvNCF	11465.29 [sec] / 3.18 [hour]	102.80 [sec] / 1.71 [min]	250

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Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 71. The results of our evaluation can be seen in Table 72 (Movielens 1M), Table 73 (Movielens HetRec), Table 74 (Frappe) and Table 75 (FilmTrust). The corresponding optimal hyperparameters are reported in Table 76 (collaborative KNNs), Table 77 (non-neural machine learning and graph based) and Table 78 (NeuRec).

Lastly, the time required to train and evaluate the models is reported in Table 79 (Movielens 1M), Table 80 (Movielens HetRec), Table 81 (Frappe) and Table 82 (FilmTrust).

Table 71. Dataset characteristics.

Dataset	Interactions	Items	Users	Density
Movielens 1M	1M	3882	6039	4.25
Movielens HetRec	855K	10109	2113	4.01
Frappe	19K	4082	957	0.48
FilmTrust	35K	2071	1508	1.14

Table 72. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 1M														
	@5					@10					@50				
	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR
Random	0.0090	0.0013	0.0044	0.0023	0.0209	0.0089	0.0026	0.0029	0.0036	0.0257	0.0091	0.0131	0.0016	0.0101	0.0346
TopPop	0.2105	0.0402	0.1531	0.0689	0.3621	0.1832	0.0685	0.1168	0.0939	0.3793	0.1127	0.1985	0.0734	0.1732	0.3912
UserKNN CF cosine	**0.4075**	**0.1034**	**0.3298**	**0.1626**	**0.6335**	**0.3468**	**0.1667**	**0.2616**	**0.2158**	**0.6441**	**0.1972**	**0.4022**	**0.1910**	**0.3583**	**0.6482**
UserKNN CF dice	**0.4189**	**0.1055**	**0.3415**	**0.1658**	**0.6368**	**0.3583**	**0.1714**	**0.2738**	**0.2210**	**0.6475**	**0.2051**	**0.4116**	**0.2015**	**0.3672**	**0.6517**
UserKNN CF jaccard	**0.4179**	**0.1050**	**0.3406**	**0.1653**	**0.6365**	**0.3578**	**0.1705**	**0.2730**	**0.2204**	**0.6474**	**0.2038**	**0.4102**	**0.1996**	**0.3662**	**0.6515**
UserKNN CF asymmetric	**0.4212**	**0.1065**	**0.3441**	**0.1674**	**0.6399**	**0.3617**	**0.1726**	**0.2774**	**0.2230**	**0.6509**	**0.2069**	**0.4146**	**0.2047**	**0.3704**	**0.6550**
UserKNN CF tversky	**0.4042**	**0.1024**	**0.3265**	**0.1611**	**0.6277**	**0.3410**	**0.1647**	**0.2571**	**0.2132**	**0.6386**	**0.1940**	**0.3968**	**0.1873**	**0.3536**	**0.6428**
ItemKNN CF cosine	**0.4002**	**0.0987**	**0.3237**	**0.1561**	**0.6137**	**0.3432**	**0.1585**	**0.2600**	**0.2074**	**0.6247**	**0.1968**	**0.3831**	**0.1872**	**0.3452**	**0.6297**
ItemKNN CF dice	**0.3709**	**0.0854**	**0.2951**	**0.1383**	**0.5714**	**0.3215**	**0.1406**	**0.2367**	**0.1862**	**0.5845**	**0.1894**	**0.3612**	**0.1690**	**0.3211**	**0.5902**
ItemKNN CF jaccard	**0.3747**	**0.0875**	**0.2982**	**0.1401**	**0.5751**	**0.3219**	**0.1407**	**0.2376**	**0.1869**	**0.5870**	**0.1869**	**0.3559**	**0.1676**	**0.3187**	**0.5928**
ItemKNN CF asymmetric	**0.3995**	**0.0984**	**0.3244**	**0.1563**	**0.6179**	**0.3452**	**0.1590**	**0.2618**	**0.2084**	**0.6293**	**0.1978**	**0.3865**	**0.1886**	**0.3474**	**0.6341**
ItemKNN CF tversky	**0.3718**	**0.0867**	**0.2998**	**0.1414**	**0.5878**	**0.3116**	**0.1359**	**0.2343**	**0.1846**	**0.5985**	0.1750	**0.3300**	**0.1582**	**0.3037**	**0.6041**
P3alpha	**0.4041**	**0.1007**	**0.3286**	**0.1596**	**0.6250**	**0.3456**	**0.1627**	**0.2627**	**0.2121**	**0.6362**	**0.1988**	**0.3945**	**0.1919**	**0.3538**	**0.6410**
RP3beta	**0.4080**	**0.1007**	**0.3325**	**0.1602**	**0.6260**	**0.3508**	**0.1639**	**0.2676**	**0.2137**	**0.6374**	**0.2012**	**0.3938**	**0.1949**	**0.3551**	**0.6420**
EASE R	**0.4360**	**0.1073**	**0.3608**	**0.1697**	**0.6475**	**0.3745**	**0.1731**	**0.2923**	**0.2259**	**0.6585**	**0.2208**	**0.4263**	**0.2190**	**0.3820**	**0.6624**
SLIM BPR	**0.3964**	**0.1034**	**0.3161**	**0.1606**	**0.6222**	**0.3358**	**0.1663**	**0.2494**	**0.2128**	**0.6335**	**0.1968**	**0.4048**	**0.1892**	**0.3568**	**0.6379**
SLIMElasticNet	**0.4437**	**0.1106**	**0.3692**	**0.1749**	**0.6578**	**0.3813**	**0.1770**	**0.3003**	**0.2321**	**0.6679**	**0.2234**	**0.4333**	**0.2259**	**0.3902**	**0.6720**
MF BPR	**0.3576**	**0.0830**	**0.2812**	**0.1340**	**0.5628**	**0.3073**	**0.1384**	**0.2217**	**0.1807**	**0.5768**	**0.1828**	**0.3575**	**0.1593**	**0.3128**	**0.5825**
MF FunkSVD	**0.3936**	**0.0927**	**0.3154**	**0.1479**	**0.6000**	**0.3458**	**0.1555**	**0.2572**	**0.2014**	**0.6125**	**0.2090**	**0.4074**	**0.1926**	**0.3541**	**0.6176**
PureSVD	**0.4123**	**0.0987**	**0.3371**	**0.1586**	**0.6266**	**0.3575**	**0.1624**	**0.2722**	**0.2132**	**0.6380**	**0.2133**	**0.4089**	**0.2033**	**0.3651**	**0.6427**
NMF	**0.3811**	**0.0891**	**0.3017**	**0.1430**	**0.5817**	**0.3338**	**0.1499**	**0.2442**	**0.1948**	**0.5947**	**0.2070**	**0.4047**	**0.1872**	**0.3489**	**0.6005**
IALS	**0.4164**	**0.1036**	**0.3373**	**0.1635**	**0.6327**	**0.3628**	**0.1702**	**0.2743**	**0.2200**	**0.6443**	**0.2180**	**0.4265**	**0.2104**	**0.3774**	**0.6483**
INeuRec	0.3280	0.0663	0.2554	0.1110	0.5003	0.2839	0.1094	0.2027	0.1500	0.5129	0.1755	0.3048	0.1397	0.2719	0.5206
UNeuRec	0.2098	0.0395	0.1560	0.0684	0.3663	0.1856	0.0688	0.1199	0.0944	0.3852	0.1143	0.2002	0.0750	0.1743	0.3968

Table 73. Experimental results on the metrics and cutoffs reported in the original paper.

	Hetrec														
	@5					@10					@50				
	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR
Random	0.0093	0.0005	0.0039	0.0011	0.0189	0.0095	0.0012	0.0026	0.0019	0.0246	0.0088	0.0049	0.0011	0.0053	0.0336
TopPop	0.4556	0.0408	0.3850	0.0889	0.6264	0.4057	0.0712	0.3137	0.1237	0.6368	0.2632	0.2048	0.1768	0.2326	0.6406
UserKNN CF cosine	**0.5632**	**0.0605**	**0.4977**	**0.1237**	**0.7420**	**0.4988**	**0.1001**	**0.4145**	**0.1677**	**0.7486**	0.3131	**0.2685**	**0.2413**	**0.3005**	**0.7517**
UserKNN CF dice	**0.5714**	**0.0614**	**0.5079**	**0.1250**	**0.7465**	**0.5087**	**0.1015**	**0.4279**	**0.1698**	**0.7525**	**0.3237**	**0.2736**	**0.2538**	**0.3066**	**0.7560**
UserKNN CF jaccard	**0.5692**	**0.0617**	**0.5063**	**0.1250**	**0.7461**	**0.5088**	**0.1016**	**0.4276**	**0.1699**	**0.7520**	**0.3233**	**0.2729**	**0.2533**	**0.3062**	**0.7554**
UserKNN CF asymmetric	**0.5729**	**0.0619**	**0.5097**	**0.1251**	**0.7449**	**0.5151**	**0.1012**	**0.4346**	**0.1702**	**0.7504**	**0.3283**	**0.2750**	**0.2597**	**0.3086**	**0.7537**
UserKNN CF tversky	**0.5670**	**0.0612**	**0.5039**	**0.1245**	**0.7474**	**0.5044**	**0.1014**	**0.4216**	**0.1693**	**0.7538**	**0.3195**	**0.2713**	**0.2487**	**0.3044**	**0.7571**
ItemKNN CF cosine	0.5405	**0.0528**	0.4747	**0.1119**	**0.7096**	0.4750	**0.0873**	0.3922	**0.1519**	**0.7157**	0.2971	**0.2427**	0.2219	0.2759	**0.7196**
ItemKNN CF dice	0.5371	**0.0513**	0.4672	**0.1098**	0.6993	0.4741	**0.0867**	0.3880	**0.1504**	0.7062	0.2981	**0.2425**	0.2198	0.2754	0.7101
ItemKNN CF jaccard	0.5200	**0.0504**	0.4537	**0.1078**	0.6993	0.4560	0.0838	0.3711	0.1462	0.7063	0.2857	0.2316	0.2068	0.2647	0.7101
ItemKNN CF asymmetric	**0.5676**	**0.0572**	**0.5041**	**0.1210**	**0.7426**	**0.4996**	**0.0941**	**0.4165**	**0.1635**	**0.7494**	**0.3185**	**0.2437**	**0.2439**	**0.2900**	**0.7520**
ItemKNN CF tversky	0.5408	**0.0539**	0.4747	**0.1150**	**0.7234**	0.4791	**0.0898**	0.3923	**0.1563**	**0.7295**	0.3082	**0.2522**	0.2292	**0.2863**	**0.7332**
P3alpha	0.5032	**0.0519**	0.4351	0.1070	0.6831	0.4501	**0.0905**	0.3592	0.1484	0.6923	0.2861	**0.2481**	0.2057	0.2714	0.6963
RP3beta	**0.5464**	**0.0558**	0.4692	**0.1159**	**0.7110**	**0.4970**	**0.0950**	0.4013	**0.1607**	**0.7172**	0.2936	0.2246	0.2215	0.2727	**0.7201**
EASE R	**0.6253**	**0.0662**	**0.5673**	**0.1358**	**0.7790**	**0.5610**	**0.1094**	**0.4865**	**0.1853**	**0.7837**	**0.3621**	**0.2949**	**0.3010**	**0.3355**	**0.7865**
SLIM BPR	0.5196	**0.0574**	0.4383	**0.1136**	0.6929	0.4709	**0.0989**	0.3701	**0.1581**	0.6999	0.3050	**0.2656**	0.2258	**0.2895**	0.7030
SLIMElasticNet	**0.6283**	**0.0670**	**0.5732**	**0.1379**	**0.7879**	**0.5612**	**0.1103**	**0.4882**	**0.1874**	**0.7933**	**0.3549**	**0.2906**	**0.2958**	**0.3333**	**0.7959**
MF BPR	0.4204	0.0360	0.3493	0.0811	0.6028	0.3750	0.0659	0.2805	0.1143	0.6138	0.2533	0.1983	0.1608	0.2215	0.6189
MF FunkSVD	0.4882	0.0447	0.4088	0.0947	0.6446	0.4520	0.0820	0.3525	0.1364	0.6538	0.3145	**0.2541**	0.2240	0.2730	0.6585
PureSVD	**0.5977**	**0.0601**	**0.5364**	**0.1271**	**0.7524**	**0.5369**	**0.1010**	**0.4548**	**0.1746**	**0.7578**	**0.3521**	**0.2849**	**0.2784**	**0.3237**	**0.7609**
NMF	0.5432	**0.0570**	0.4686	**0.1180**	**0.7108**	**0.4892**	**0.0964**	0.3941	**0.1632**	**0.7165**	**0.3193**	**0.2675**	**0.2384**	**0.3023**	**0.7197**
IALS	**0.5900**	**0.0609**	**0.5253**	**0.1281**	**0.7542**	**0.5322**	**0.1039**	**0.4456**	**0.1770**	**0.7593**	**0.3464**	**0.2857**	**0.2715**	**0.3243**	**0.7620**
INeuRec	0.5435	0.0489	0.4797	0.1076	0.7021	0.4884	0.0844	0.4047	0.1493	0.7094	0.3151	0.2402	0.2371	0.2769	0.7129
UNeuRec	0.4467	0.0397	0.3785	0.0877	0.6278	0.3973	0.0693	0.3077	0.1216	0.6365	0.2599	0.2029	0.1731	0.2299	0.6413

Table 74. Experimental results on the metrics and cutoffs reported in the original paper.

	Frappe														
	@5					@10					@50				
	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR
Random	0.0014	0.0019	0.0011	0.0014	0.0036	0.0015	0.0039	0.0010	0.0022	0.0046	0.0015	0.0121	0.0013	0.0054	0.0069
TopPop	0.1332	0.2010	0.1441	0.1842	0.3183	0.0920	0.2602	0.1411	0.2118	0.3302	0.0383	0.4325	0.1530	0.2721	0.3387
UserKNN CF cosine	0.1888	**0.2243**	0.1943	0.2213	0.3880	0.1339	0.2929	0.1845	0.2578	0.3980	**0.0480**	**0.4635**	0.1940	**0.3207**	0.4042
UserKNN CF dice	0.1810	0.2175	0.1899	0.2168	0.3821	0.1279	0.2873	0.1813	0.2532	0.3928	0.0467	**0.4541**	0.1906	**0.3149**	0.3991
UserKNN CF jaccard	0.1844	**0.2248**	0.1923	0.2203	0.3843	0.1291	0.2871	0.1823	0.2540	0.3937	0.0472	**0.4568**	0.1918	**0.3167**	0.4001
UserKNN CF asymmetric	0.1899	**0.2267**	0.1965	0.2232	0.3893	0.1349	0.2939	0.1873	0.2592	0.3979	0.0477	**0.4564**	0.1944	**0.3193**	0.4045
UserKNN CF tversky	0.1961	**0.2225**	0.2037	0.2231	0.3893	0.1401	**0.2965**	**0.1912**	**0.2619**	0.3996	**0.0490**	**0.4613**	**0.1987**	**0.3233**	0.4057
ItemKNN CF cosine	0.1947	0.2192	0.2032	**0.2243**	0.3980	0.1342	0.2780	0.1877	0.2564	0.4059	**0.0484**	**0.4524**	**0.1965**	**0.3198**	0.4120
ItemKNN CF dice	0.1779	0.2075	0.1856	0.2094	0.3743	0.1198	0.2643	0.1724	0.2390	0.3833	0.0453	0.4406	0.1800	0.3018	0.3911
ItemKNN CF jaccard	0.1785	0.2094	0.1855	0.2095	0.3726	0.1196	0.2669	0.1719	0.2389	0.3817	0.0452	0.4385	0.1792	0.3006	0.3891
ItemKNN CF asymmetric	0.1852	**0.2261**	0.1964	**0.2236**	0.3882	0.1263	0.2817	0.1839	0.2538	0.3970	0.0473	**0.4554**	0.1940	**0.3178**	0.4037
ItemKNN CF tversky	0.1777	0.2139	0.1840	0.2117	0.3762	0.1212	0.2698	0.1729	0.2414	0.3840	0.0462	0.4434	0.1814	0.3042	0.3912
P3alpha	0.1933	**0.2322**	0.1939	**0.2254**	0.3838	0.1447	**0.3050**	**0.1899**	**0.2664**	0.3932	**0.0511**	**0.4699**	**0.2029**	**0.3296**	0.3984
RP3beta	0.2059	**0.2349**	**0.2084**	**0.2341**	**0.4074**	**0.1486**	**0.3067**	**0.1981**	**0.2742**	**0.4163**	**0.0507**	**0.4631**	**0.2084**	**0.3341**	**0.4208**
EASE R	0.1978	**0.2252**	0.1997	**0.2245**	0.3877	0.1444	0.2927	**0.1915**	**0.2630**	0.3960	**0.0509**	**0.4482**	**0.2022**	**0.3242**	0.4010
SLIM BPR	0.1791	**0.2231**	0.1860	0.2167	0.3773	0.1272	0.2812	0.1771	0.2493	0.3865	0.0456	**0.4464**	0.1860	0.3091	0.3931
SLIMElasticNet	0.2014	**0.2299**	0.2023	**0.2285**	0.3943	0.1464	**0.3028**	**0.1938**	**0.2686**	0.4030	**0.0516**	**0.4665**	**0.2054**	**0.3312**	0.4076
MF BPR	0.1209	0.1429	0.1045	0.1333	0.2456	0.0933	0.2101	0.1036	0.1664	0.2604	0.0396	0.3914	0.1174	0.2316	0.2701
MF FunkSVD	0.1601	**0.2214**	0.1600	0.2016	0.3431	0.1205	**0.2973**	0.1597	0.2410	0.3569	0.0467	**0.4726**	0.1769	0.3069	0.3624
PureSVD	0.1282	0.1753	0.1362	0.1687	0.3064	0.0983	0.2386	0.1356	0.2017	0.3200	0.0375	0.3993	0.1443	0.2558	0.3263
NMF	0.1439	0.1008	0.1310	0.1197	0.2378	0.1047	0.1389	0.1118	0.1436	0.2434	0.0336	0.2282	0.1088	0.1784	0.2492
IALS	0.1774	0.1804	0.1768	0.1918	0.3503	0.1335	0.2534	0.1690	0.2313	0.3599	0.0454	0.4016	0.1750	0.2867	0.3657
INeuRec	**0.2117**	0.2196	0.2073	0.2235	0.4045	0.1479	0.2862	0.1891	0.2603	0.4116	0.0478	0.4305	0.1946	0.3133	0.4161
UNeuRec	0.1679	0.2206	0.1788	0.2100	0.3650	0.1194	0.2964	0.1731	0.2470	0.3780	0.0402	0.4448	0.1785	0.2992	0.3852

Table 75. Experimental results on the metrics and cutoffs reported in the original paper.

	Filmtrust														
	@5					@10					@50				
	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR	PREC	REC	MAP	NDCG	MRR
Random	0.0027	0.0015	0.0010	0.0014	0.0043	0.0023	0.0029	0.0008	0.0022	0.0054	0.0030	0.0266	0.0016	0.0102	0.0099
TopPop	0.4200	**0.4126**	0.4393	**0.4203**	0.6145	0.3471	**0.6351**	**0.4597**	**0.5450**	0.6273	0.0916	**0.8614**	**0.4954**	**0.6314**	0.6316
UserKNN CF cosine	**0.4349**	**0.4357**	**0.4735**	**0.4498**	**0.6496**	**0.3545**	**0.6357**	**0.4909**	**0.5677**	**0.6581**	**0.0921**	0.8247	**0.5202**	**0.6429**	**0.6615**
UserKNN CF dice	**0.4341**	**0.4339**	**0.4667**	**0.4457**	**0.6452**	**0.3512**	0.6286	**0.4822**	**0.5604**	**0.6526**	0.0917	0.8241	**0.5135**	**0.6382**	**0.6561**
UserKNN CF jaccard	**0.4354**	**0.4400**	**0.4713**	**0.4510**	**0.6492**	**0.3560**	**0.6455**	**0.4907**	**0.5712**	**0.6579**	**0.0932**	0.8524	**0.5229**	**0.6517**	**0.6620**
UserKNN CF asymmetric	**0.4322**	**0.4292**	**0.4656**	**0.4431**	**0.6431**	**0.3517**	**0.6309**	**0.4825**	**0.5608**	**0.6515**	**0.0919**	0.8257	**0.5139**	**0.6386**	**0.6554**
UserKNN CF tversky	**0.4338**	**0.4335**	**0.4646**	**0.4436**	**0.6434**	**0.3519**	**0.6328**	**0.4805**	**0.5601**	**0.6515**	**0.0918**	0.8267	**0.5116**	**0.6372**	**0.6545**
ItemKNN CF cosine	**0.4268**	**0.4247**	**0.4551**	**0.4354**	**0.6332**	**0.3484**	**0.6303**	**0.4724**	**0.5540**	**0.6432**	0.0916	0.8478	**0.5072**	**0.6380**	**0.6470**
ItemKNN CF dice	**0.4264**	**0.4205**	**0.4559**	**0.4355**	**0.6388**	**0.3507**	**0.6338**	**0.4753**	**0.5577**	**0.6492**	0.0917	0.8473	**0.5083**	**0.6394**	**0.6527**
ItemKNN CF jaccard	**0.4259**	**0.4202**	**0.4561**	**0.4358**	**0.6407**	**0.3511**	**0.6344**	**0.4758**	**0.5585**	**0.6512**	0.0917	0.8473	**0.5086**	**0.6398**	**0.6548**
ItemKNN CF asymmetric	**0.4286**	**0.4238**	**0.4564**	**0.4360**	**0.6348**	**0.3490**	**0.6303**	**0.4734**	**0.5548**	**0.6447**	**0.0923**	0.8516	**0.5081**	**0.6400**	**0.6487**
ItemKNN CF tversky	**0.4262**	**0.4208**	**0.4566**	**0.4365**	**0.6413**	**0.3509**	**0.6342**	**0.4763**	**0.5587**	**0.6513**	0.0917	0.8473	**0.5092**	**0.6402**	**0.6549**
P3alpha	**0.4240**	**0.4199**	**0.4526**	**0.4321**	**0.6351**	**0.3500**	**0.6343**	**0.4719**	**0.5550**	**0.6467**	**0.0938**	**0.8605**	**0.5080**	**0.6430**	**0.6511**
RP3beta	**0.4373**	**0.4365**	**0.4709**	**0.4492**	**0.6537**	**0.3575**	**0.6436**	**0.4880**	**0.5701**	**0.6631**	**0.0950**	**0.8647**	**0.5228**	**0.6562**	**0.6674**
EASE R	**0.4374**	**0.4395**	**0.4747**	**0.4531**	**0.6571**	**0.3551**	**0.6443**	**0.4916**	**0.5722**	**0.6663**	**0.0923**	0.8511	**0.5237**	**0.6520**	**0.6700**
SLIM BPR	**0.4327**	**0.4351**	**0.4643**	**0.4455**	**0.6465**	**0.3522**	**0.6399**	**0.4825**	**0.5647**	**0.6549**	**0.0922**	0.8529	**0.5166**	**0.6472**	**0.6589**
SLIMElasticNet	**0.4418**	**0.4417**	**0.4803**	**0.4572**	**0.6600**	**0.3583**	**0.6566**	**0.4983**	**0.5796**	**0.6708**	**0.0944**	**0.8631**	**0.5309**	**0.6604**	**0.6742**
MF BPR	0.4115	0.4047	0.4309	0.4114	0.5979	0.3433	0.6156	0.4519	0.5330	0.6088	0.0902	0.8433	0.4877	0.6193	0.6138
MF FunkSVD	0.4112	0.4004	0.4148	0.3972	0.5781	0.3452	0.6265	0.4378	0.5245	0.5917	0.0906	0.8486	0.4731	0.6095	0.5957
PureSVD	**0.4292**	**0.4255**	**0.4563**	**0.4366**	**0.6366**	**0.3478**	0.6255	**0.4724**	**0.5526**	**0.6453**	0.0912	0.8301	**0.5041**	**0.6322**	**0.6490**
NMF	0.2721	0.2407	0.2769	0.2584	0.4131	0.1983	0.3332	0.2443	0.3123	0.4234	0.0684	0.5484	0.2744	0.3968	0.4315
IALS	0.4038	0.3855	0.4240	0.4028	0.6021	0.3342	0.5920	0.4400	0.5201	0.6137	0.0889	0.8124	0.4720	0.6043	0.6193
INeuRec	0.4221	0.4089	0.4398	0.4196	0.6151	0.3466	0.6187	0.4577	0.5398	0.6261	0.0918	0.8556	0.4935	0.6285	0.6310
UNeuRec	0.4174	0.4062	0.4384	0.4181	0.6157	0.3472	0.6291	0.4596	0.5436	0.6286	0.0912	0.8570	0.4952	0.6304	0.6337

Table 76. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Hetrec	Frappe	Filmtrust
UserKNN CF cosine	topK	235	490	565	609
	shrink	3	921	749	0
	similarity	cosine	cosine	cosine	cosine
	normalize	True	True	True	True
	feature weighting	TF-IDF	TF-IDF	TF-IDF	none
UserKNN CF dice	topK	224	593	182	277
	shrink	0	336	4	1
	similarity	dice	dice	dice	dice
	normalize	False	True	False	False
UserKNN CF jaccard	topK	237	510	244	290
	shrink	0	5	7	0
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	False	False	True	False
UserKNN CF asymmetric	topK	398	594	193	279
	shrink	0	1000	348	306
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	0.0000	2.0000	0.0744	0.3358
	feature weighting	TF-IDF	TF-IDF	TF-IDF	TF-IDF
UserKNN CF tversky	topK	309	598	580	358
	shrink	0	32	169	18
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	0.0000	0.0113	2.0000	1.9153
	tversky beta	2.0000	0.2846	2.0000	1.5318
ItemKNN CF cosine	topK	1000	320	307	264
	shrink	524	497	1	1000
	similarity	cosine	cosine	cosine	cosine
	normalize	True	False	True	True
	feature weighting	TF-IDF	TF-IDF	TF-IDF	TF-IDF
ItemKNN CF dice	topK	973	676	99	103
	shrink	273	746	82	226
	similarity	dice	dice	dice	dice
	normalize	True	True	True	True
ItemKNN CF jaccard	topK	763	301	112	87
	shrink	304	734	59	974
	similarity	jaccard	jaccard	jaccard	jaccard
	normalize	True	True	True	True
ItemKNN CF asymmetric	topK	779	1000	258	5
	shrink	1000	1000	0	1000
	similarity	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True
	asymmetric alpha	0.2985	0.0000	0.4750	0.0000
	feature weighting	TF-IDF	TF-IDF	TF-IDF	TF-IDF
ItemKNN CF tversky	topK	258	1000	331	30
	shrink	196	859	0	394
	similarity	tversky	tversky	tversky	tversky
	normalize	True	True	True	True
	tversky alpha	0.3885	0.9712	0.9659	0.7213
	tversky beta	1.6358	0.6517	2.0000	1.9521

Table 77. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Hetrec	Frappe	Filmtrust
$P^3\alpha$	topK	347	270	162	857
	alpha	0.6960	1.5154	1.4534	1.8765
	normalize similarity	False	True	True	True
$RP^3\beta$	topK	640	263	109	5
	alpha	0.6964	1.0001	1.1222	0.6525
	beta	0.2177	0.4673	0.1090	0.3863
	normalize similarity	False	True	True	False
$EASE^R$	l2 norm	2.72E+02	2.37E+03	2.31E+03	1.77E+03
SLIM BPR	topK	1000	1000	1000	1000
	epochs	25	35	195	160
	symmetric	True	True	True	True
	sgd mode	adagrad	adagrad	sgd	sgd
	lambda i	1.00E-02	1.00E-02	1.00E-02	1.00E-02
	lambda j	1.00E-02	1.00E-05	1.00E-02	1.00E-02
	learning rate	1.00E-04	3.60E-02	8.77E-03	1.55E-02
SLIMElasticNet	topK	671	458	659	344
	l1 ratio	1.13E-05	1.00E-05	1.19E-03	3.19E-03
	alpha	0.3182	0.1082	0.1394	0.5223
MF BPR	sgd mode	adagrad	adam	adagrad	adagrad
	epochs	95	135	1005	400
	num factors	200	104	200	1
	batch size	256	2	16	8
	positive reg	3.97E-03	4.85E-05	2.45E-03	1.00E-05
	negative reg	1.00E-02	1.00E-05	1.00E-02	1.00E-02
	learning rate	8.84E-02	4.67E-04	3.37E-02	4.08E-02
MF FunkSVD	sgd mode	adagrad	adam	adam	adam
	epochs	170	70	420	65
	use bias	True	False	False	True
	batch size	1	8	128	1024
	num factors	200	1	32	63
	item reg	1.00E-05	1.00E-02	1.05E-05	1.22E-04
	user reg	1.00E-02	1.00E-05	7.21E-04	9.95E-04
	learning rate	1.00E-01	1.31E-03	1.95E-04	3.29E-04
	negative quota	0.5000	0.1059	0.1103	0.1179
PureSVD	num factors	1	5	30	43
NMF	num factors	42	208	62	139
	solver	coord. descent	mult. update	mult. update	coord. descent
	init type	nndsvda	nndsvda	random	nndsvda
	beta loss	frobenius	frobenius	kullback-leibler	frobenius
iALS	num factors	22	10	35	61
	confidence scaling	log	linear	log	linear
	alpha	0.0045	0.3831	0.8507	0.0094
	epsilon	0.1795	0.0984	0.3278	9.7751
	reg	1.45E-03	1.38E-03	1.41E-03	1.50E-05
	epochs	5	15	60	60

Table 78. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Hetrec	Frappe	Filmtrust
INeuRec	num neurons	300	150	300	300
	num factors	50	40	50	50
	dropout percentage	0.0300	0.0000	0.0300	0.0300
	learning rate	1.00E-04	5.00E-05	1.00E-04	1.00E-04
	regularization rate	1.00E-02	1.00E-01	1.00E-01	1.00E-01
	epochs	50	25	5	10
	batch size	1024	1024	1024	1024
UNeuRec	num neurons	300	150	300	300
	num factors	50	40	50	50
	dropout percentage	0.0300	0.0000	0.0300	0.0300
	learning rate	1.00E-04	5.00E-05	1.00E-04	1.00E-04
	regularization rate	1.00E-02	1.00E-01	1.00E-01	1.00E-01
	epochs	5	5	50	145
	batch size	1024	1024	1024	1024

Table 79. Comparison of the computation time for the different algorithms.

	Movielens 1M		
	Train time	Recommendation Time	[usr/s]
Random	0.02 [sec]	52.96 [sec]	114
TopPop	0.03 [sec]	51.76 [sec]	117
UserKNN CF cosine	3.50 ± 0.15 [sec]	54.05 ± 0.34 [sec]	112
UserKNN CF dice	3.32 ± 0.24 [sec]	53.36 ± 0.64 [sec]	115
UserKNN CF jaccard	3.30 ± 0.22 [sec]	53.55 ± 0.68 [sec]	114
UserKNN CF asymmetric	3.35 ± 0.25 [sec]	53.54 ± 0.31 [sec]	113
UserKNN CF tversky	3.38 ± 0.27 [sec]	53.32 ± 0.90 [sec]	112
ItemKNN CF cosine	1.58 ± 0.14 [sec]	54.81 ± 1.12 [sec]	111
ItemKNN CF dice	1.53 ± 0.12 [sec]	54.57 ± 1.19 [sec]	114
ItemKNN CF jaccard	1.51 ± 0.13 [sec]	53.87 ± 1.13 [sec]	114
ItemKNN CF asymmetric	1.52 ± 0.17 [sec]	53.16 ± 1.05 [sec]	112
ItemKNN CF tversky	1.52 ± 0.15 [sec]	53.93 ± 0.54 [sec]	113
$P^3\alpha$	3.88 ± 1.58 [sec]	52.34 ± 0.77 [sec]	116
$RP^3\beta$	4.49 ± 1.98 [sec]	51.69 ± 0.88 [sec]	117
$EASE^R$	7.50 ± 0.04 [sec]	53.57 ± 0.02 [sec]	113
SLIM BPR	540.48 [sec] / 9.01 ± 9.45 [min]	53.73 ± 1.12 [sec]	110
SLIMElasticNet	157.83 [sec] / 2.63 ± 1.60 [min]	51.36 ± 2.17 [sec]	112
MF BPR	403.10 [sec] / 6.72 ± 5.21 [min]	51.98 ± 0.87 [sec]	114
MF FunkSVD	1471.34 [sec] / 24.52 ± 36.83 [min]	51.81 ± 0.17 [sec]	116
PureSVD	0.70 ± 0.66 [sec]	52.60 ± 0.15 [sec]	114
NMF	295.91 [sec] / 4.93 ± 3.69 [min]	52.88 ± 0.17 [sec]	114
iALS	350.79 [sec] / 5.85 ± 5.04 [min]	52.84 ± 0.05 [sec]	114
INeuRec	71409.67 [sec] / 19.84 [hour]	42.31 [sec]	143
UNeuRec	57989.25 [sec] / 16.11 [hour]	42.22 [sec]	143

Table 80. Comparison of the computation time for the different algorithms.

	Hetrec		
	Train time	Recommendation Time	[usr/s]
Random	0.02 [sec]	41.87 [sec]	50
TopPop	0.03 [sec]	40.99 [sec]	52
UserKNN CF cosine	1.12 ± 0.05 [sec]	42.23 ± 1.16 [sec]	49
UserKNN CF dice	1.15 ± 0.07 [sec]	42.47 ± 0.44 [sec]	50
UserKNN CF jaccard	1.15 ± 0.07 [sec]	42.41 ± 0.49 [sec]	50
UserKNN CF asymmetric	1.16 ± 0.08 [sec]	42.10 ± 1.37 [sec]	50
UserKNN CF tversky	1.16 ± 0.08 [sec]	42.46 ± 0.46 [sec]	50
ItemKNN CF cosine	4.34 ± 0.52 [sec]	45.85 ± 1.56 [sec]	47
ItemKNN CF dice	4.43 ± 0.59 [sec]	43.91 ± 1.37 [sec]	49
ItemKNN CF jaccard	4.38 ± 0.61 [sec]	43.30 ± 0.70 [sec]	49
ItemKNN CF asymmetric	4.14 ± 0.55 [sec]	43.05 ± 3.72 [sec]	52
ItemKNN CF tversky	4.37 ± 0.54 [sec]	43.20 ± 2.21 [sec]	51
$P^3\alpha$	16.00 ± 5.00 [sec]	41.18 ± 0.26 [sec]	51
$RP^3\beta$	13.93 ± 6.45 [sec]	41.57 ± 0.99 [sec]	52
$EASE^R$	86.06 [sec] / 1.43 ± 0.00 [min]	44.61 ± 0.23 [sec]	47
SLIM BPR	265.23 [sec] / 4.42 ± 3.41 [min]	43.10 ± 0.64 [sec]	48
SLIMElasticNet	310.27 [sec] / 5.17 ± 2.36 [min]	42.49 ± 1.28 [sec]	49
MF BPR	80.12 [sec] / 1.34 ± 1.07 [min]	42.17 ± 0.28 [sec]	50
MF FunkSVD	208.95 [sec] / 3.48 ± 5.74 [min]	42.47 ± 0.20 [sec]	50
PureSVD	0.59 ± 0.40 [sec]	42.15 ± 0.04 [sec]	50
NMF	326.21 [sec] / 5.44 ± 4.32 [min]	42.71 ± 0.84 [sec]	50
iALS	328.16 [sec] / 5.47 ± 5.00 [min]	42.58 ± 0.05 [sec]	50
INeuRec	50152.19 [sec] / 13.93 [hour]	35.26 [sec]	60
UNeuRec	74545.39 [sec] / 20.71 [hour]	39.53 [sec]	53

Table 81. Comparison of the computation time for the different algorithms.

	Frappe		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	5.78 [sec]	124
TopPop	0.00 [sec]	4.94 [sec]	145
UserKNN CF cosine	0.06 ± 0.01 [sec]	5.07 ± 0.03 [sec]	141
UserKNN CF dice	0.06 ± 0.01 [sec]	5.13 ± 0.03 [sec]	141
UserKNN CF jaccard	0.06 ± 0.01 [sec]	5.09 ± 0.03 [sec]	141
UserKNN CF asymmetric	0.06 ± 0.01 [sec]	5.09 ± 0.01 [sec]	140
UserKNN CF tversky	0.06 ± 0.01 [sec]	5.07 ± 0.03 [sec]	141
ItemKNN CF cosine	0.24 ± 0.01 [sec]	5.00 ± 0.02 [sec]	143
ItemKNN CF dice	0.24 ± 0.01 [sec]	4.98 ± 0.01 [sec]	143
ItemKNN CF jaccard	0.24 ± 0.01 [sec]	4.98 ± 0.01 [sec]	144
ItemKNN CF asymmetric	0.24 ± 0.01 [sec]	4.99 ± 0.02 [sec]	143
ItemKNN CF tversky	0.25 ± 0.01 [sec]	4.99 ± 0.00 [sec]	144
$P^3\alpha$	0.84 ± 0.13 [sec]	4.93 ± 0.03 [sec]	145
$RP^3\beta$	0.88 ± 0.19 [sec]	4.96 ± 0.03 [sec]	144
$EASE^R$	6.22 ± 0.04 [sec]	5.00 ± 0.01 [sec]	143
SLIM BPR	22.86 ± 9.88 [sec]	4.96 ± 0.05 [sec]	144
SLIMElasticNet	26.27 ± 3.82 [sec]	5.01 ± 0.01 [sec]	143
MF BPR	21.62 ± 41.61 [sec]	5.01 ± 0.03 [sec]	143
MF FunkSVD	39.35 ± 32.47 [sec]	5.05 ± 0.03 [sec]	141
PureSVD	0.06 ± 0.09 [sec]	4.93 ± 0.02 [sec]	145
NMF	24.63 ± 19.89 [sec]	5.01 ± 0.04 [sec]	144
iALS	138.27 [sec] / 2.30 ± 2.19 [min]	5.17 ± 0.18 [sec]	142
INeuRec	825.96 [sec] / 13.77 [min]	4.13 [sec]	174
UNeuRec	356.02 [sec] / 5.93 [min]	4.12 [sec]	174

Table 82. Comparison of the computation time for the different algorithms.

	Filmtrust		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	6.43 [sec]	197
TopPop	0.00 [sec]	6.21 [sec]	204
UserKNN CF cosine	0.19 ± 0.03 [sec]	6.41 ± 0.07 [sec]	196
UserKNN CF dice	0.20 ± 0.04 [sec]	6.47 ± 0.05 [sec]	195
UserKNN CF jaccard	0.20 ± 0.03 [sec]	6.46 ± 0.02 [sec]	197
UserKNN CF asymmetric	0.19 ± 0.04 [sec]	6.47 ± 0.06 [sec]	196
UserKNN CF tversky	0.20 ± 0.04 [sec]	6.49 ± 0.01 [sec]	195
ItemKNN CF cosine	0.10 ± 0.01 [sec]	6.33 ± 0.05 [sec]	200
ItemKNN CF dice	0.11 ± 0.01 [sec]	6.35 ± 0.00 [sec]	199
ItemKNN CF jaccard	0.10 ± 0.01 [sec]	6.33 ± 0.02 [sec]	200
ItemKNN CF asymmetric	0.11 ± 0.01 [sec]	6.33 ± 0.05 [sec]	199
ItemKNN CF tversky	0.11 ± 0.01 [sec]	6.36 ± 0.00 [sec]	199
$P^3\alpha$	0.55 ± 0.11 [sec]	6.31 ± 0.04 [sec]	202
$RP^3\beta$	0.58 ± 0.13 [sec]	6.31 ± 0.03 [sec]	201
$EASE^R$	0.97 ± 0.03 [sec]	6.26 ± 0.07 [sec]	201
SLIM BPR	14.96 ± 9.29 [sec]	6.34 ± 0.06 [sec]	199
SLIMElasticNet	9.53 ± 1.99 [sec]	6.31 ± 0.04 [sec]	201
MF BPR	38.98 ± 45.37 [sec]	6.23 ± 0.14 [sec]	200
MF FunkSVD	31.97 ± 39.84 [sec]	6.26 ± 0.02 [sec]	202
PureSVD	0.05 ± 0.06 [sec]	6.15 ± 0.14 [sec]	202
NMF	32.20 ± 35.82 [sec]	6.32 ± 0.17 [sec]	197
iALS	58.77 ± 37.14 [sec]	6.25 ± 0.05 [sec]	201
INeuRec	424.72 [sec] / 7.08 [min]	5.07 [sec]	250
UNeuRec	230.86 [sec] / 3.85 [min]	5.11 [sec]	248

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Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 83. The results of our evaluation can be seen in Table 84 (Amazon Music original), Table 85 (Amazon Music ours), Table 86 (Amazon Movie), Table 87 (Movielens 100k) and Table 88 (Movielens 1M). The corresponding optimal hyperparameters are reported in Table 89 (collaborative KNNs), Table 90 (non-neural machine learning and graph based) and Table 91 (NeuRec).

Lastly, the time required to train and evaluate the models is reported in Table 92 (Amazon Music original), Table 93 (Amazon Music ours), Table 94 (Amazon Movie), Table 95 (Movielens 100k) and Table 96 (Movielens 1M).

Table 83. Dataset characteristics.

Dataset	Interactions	Items	Users	Density
Amazon Music original	46.5K	18813	844	0.293
Amazon Music ours	37K	23184	844	0.189
Amazon Movie	878K	83512	15067	0.070
Movielens 100k	100K	1682	943	6.305
Movielens 1M	1M	3706	6040	4.468

Table 84. Experimental results on the metrics and cutoffs reported in the original paper.

	Amazon Music original	
	HR@10	NDCG@10
Random	0.0924	0.0380
TopPop	0.4348	0.2490
UserKNN CF cosine	**0.5521**	**0.4050**
UserKNN CF dice	0.5403	0.3854
UserKNN CF jaccard	0.5450	0.3860
UserKNN CF asymmetric	**0.5509**	**0.4052**
UserKNN CF tversky	0.5379	0.3856
ItemKNN CF cosine	0.5320	**0.3943**
ItemKNN CF dice	0.5296	0.3803
ItemKNN CF jaccard	0.5284	0.3786
ItemKNN CF asymmetric	0.5415	**0.3917**
ItemKNN CF tversky	0.5273	0.3771
$P^3\alpha$	**0.5509**	**0.3976**
$RP^3\beta$	**0.5486**	**0.3968**
$EASE^R$	0.5284	**0.3893**
SLIM BPR	0.5379	0.3763
SLIMElasticNet	0.5367	**0.3925**
MF BPR	0.4265	0.3063
MF FunkSVD	0.4467	0.3215
PureSVD	0.4502	0.3386
NMF	0.5130	0.3557
iALS	**0.5498**	**0.4022**
DMF normalized cross entropy	0.5474	0.3891
DMF binary cross entropy	0.5427	0.3850

Table 85. Experimental results on the metrics and cutoffs reported in the original paper.

	Amazon Music ours	
	HR@10	NDCG@10
Random	0.1019	0.0458
TopPop	0.5201	0.3007
UserKNN CF cosine	**0.6754**	**0.4976**
UserKNN CF dice	0.6600	0.4751
UserKNN CF jaccard	0.6588	0.4741
UserKNN CF asymmetric	**0.6742**	**0.4948**
UserKNN CF tversky	0.6505	0.4765
ItemKNN CF cosine	0.6647	**0.4884**
ItemKNN CF dice	0.6528	0.4699
ItemKNN CF jaccard	0.6564	0.4722
ItemKNN CF asymmetric	0.6659	**0.4859**
ItemKNN CF tversky	0.6445	0.4655
$P^3\alpha$	0.6576	**0.4816**
$RP^3\beta$	**0.6742**	**0.4909**
$EASE^R$	-	-
SLIM BPR	0.6671	0.4714
SLIMElasticNet	0.6469	0.4746
MF BPR	0.5545	0.3750
MF FunkSVD	0.5569	0.3913
PureSVD	0.5912	0.4189
NMF	0.6552	0.4490
iALS	0.6600	**0.4879**
DMF normalized cross entropy	0.6718	0.4815
DMF binary cross entropy	0.6659	0.4815

Table 86. Experimental results on the metrics and cutoffs reported in the original paper.

	Amazon Movie	
	HR@10	NDCG@10
Random	0.1057	0.0478
TopPop	0.5799	0.3490
UserKNN CF cosine	0.7214	0.5020
UserKNN CF dice	0.7063	0.4962
UserKNN CF jaccard	0.7064	0.4967
UserKNN CF asymmetric	0.7212	0.5020
UserKNN CF tversky	0.7033	0.4952
ItemKNN CF cosine	0.6794	0.4759
ItemKNN CF dice	0.6948	0.4869
ItemKNN CF jaccard	0.6970	0.4901
ItemKNN CF asymmetric	0.6983	0.4913
ItemKNN CF tversky	0.6658	0.4788
$P^3\alpha$	0.6971	0.5029
$RP^3\beta$	0.7103	0.5077
$EASE^R$	-	-
SLIM BPR	-	-
SLIMElasticNet	0.6980	0.5005
MF BPR	0.6425	0.4162
MF FunkSVD	0.5972	0.4091
PureSVD	0.6021	0.4156
NMF	0.6251	0.4216
iALS	0.7352	0.5230
DMF normalized cross entropy	**0.7864**	**0.5447**
DMF binary cross entropy	0.7818	0.5417

Table 87. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 100k	
	HR@10	NDCG@10
Random	0.0903	0.0415
TopPop	0.4145	0.2342
UserKNN CF cosine	0.5770	0.3306
UserKNN CF dice	0.5834	0.3325
UserKNN CF jaccard	0.5760	0.3335
UserKNN CF asymmetric	0.5898	0.3387
UserKNN CF tversky	0.5802	0.3382
ItemKNN CF cosine	0.5739	0.3346
ItemKNN CF dice	0.5962	0.3484
ItemKNN CF jaccard	0.5834	0.3422
ItemKNN CF asymmetric	0.5940	0.3457
ItemKNN CF tversky	0.6026	0.3506
$P^3\alpha$	0.5717	0.3421
$RP^3\beta$	0.5685	0.3270
$EASE^R$	0.6111	0.3591
SLIM BPR	**0.6206**	0.3578
SLIMElasticNet	**0.6238**	**0.3765**
MF BPR	0.5951	0.3365
MF FunkSVD	0.5707	0.3354
PureSVD	0.5877	0.3555
NMF	0.5855	0.3515
iALS	**0.6142**	**0.3691**
DMF normalized cross entropy	0.6111	0.3637
DMF binary cross entropy	0.6026	0.3623

Table 88. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 1M	
	HR@10	NDCG@10
Random	0.0921	0.0424
TopPop	0.4418	0.2475
UserKNN CF cosine	0.6606	0.3969
UserKNN CF dice	0.6324	0.3822
UserKNN CF jaccard	0.6323	0.3828
UserKNN CF asymmetric	0.6626	0.3975
UserKNN CF tversky	0.6362	0.3840
ItemKNN CF cosine	0.6520	0.3851
ItemKNN CF dice	0.6293	0.3692
ItemKNN CF jaccard	0.6255	0.3682
ItemKNN CF asymmetric	0.6402	0.3796
ItemKNN CF tversky	0.6326	0.3757
$P^3\alpha$	0.6097	0.3639
$RP^3\beta$	0.6304	0.3726
$EASE^R$	0.6691	**0.4093**
SLIM BPR	0.6719	**0.4068**
SLIMElasticNet	**0.6825**	**0.4209**
MF BPR	0.6323	0.3729
MF FunkSVD	0.6499	0.3912
PureSVD	0.6570	0.4015
NMF	0.6422	0.3862
iALS	**0.6947**	**0.4257**
DMF normalized cross entropy	0.6782	0.4063
DMF binary cross entropy	0.6731	0.4033

Table 89. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Amazon Music original	Amazon Music ours	Amazon Movie	Movielens 100k	Movielens 1M
UserKNN CF cosine	topK	883	614	1000	159	770
	shrink	990	15	0	0	0
	similarity	cosine	cosine	cosine	cosine	cosine
	normalize	True	True	True	True	True
	feature weighting	BM25	BM25	BM25	BM25	BM25
UserKNN CF dice	topK	163	202	955	148	177
	shrink	0	6	11	5	0
	similarity	dice	dice	dice	dice	dice
	normalize	True	False	True	False	True
UserKNN CF jaccard	topK	195	204	999	100	178
	shrink	1	0	23	3	0
	similarity	jaccard	jaccard	jaccard	jaccard	jaccard
	normalize	False	True	True	True	False
UserKNN CF asymmetric	topK	651	786	1000	169	613
	shrink	846	1000	0	0	0
	similarity	asymmetric	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True	True
	asymmetric alpha	0.4426	0.7110	0.4960	0.1994	0.3317
	feature weighting	BM25	BM25	BM25	BM25	BM25
UserKNN CF tversky	topK	152	147	858	107	337
	shrink	0	92	31	0	0
	similarity	tversky	tversky	tversky	tversky	tversky
	normalize	True	True	True	True	True
	tversky alpha	2.0000	1.9995	1.0846	1.5901	2.0000
	tversky beta	2.0000	1.3750	1.8286	2.0000	2.0000
ItemKNN CF cosine	topK	929	1000	1000	303	191
	shrink	285	893	1000	0	1
	similarity	cosine	cosine	cosine	cosine	cosine
	normalize	False	True	False	True	True
	feature weighting	BM25	TF-IDF	BM25	BM25	BM25
ItemKNN CF dice	topK	232	500	845	12	66
	shrink	99	0	18	37	4
	similarity	dice	dice	dice	dice	dice
	normalize	False	False	True	False	True
ItemKNN CF jaccard	topK	726	422	582	28	63
	shrink	9	11	42	2	5
	similarity	jaccard	jaccard	jaccard	jaccard	jaccard
	normalize	True	False	False	False	True
ItemKNN CF asymmetric	topK	778	669	978	24	303
	shrink	641	1000	859	1000	0
	similarity	asymmetric	asymmetric	asymmetric	asymmetric	asymmetric
	normalize	True	True	True	True	True
	asymmetric alpha	0.2886	0.3042	0.0000	0.2911	0.3402
	feature weighting	TF-IDF	TF-IDF	none	TF-IDF	BM25
ItemKNN CF tversky	topK	207	626	360	118	58
	shrink	949	95	71	0	143
	similarity	tversky	tversky	tversky	tversky	tversky
	normalize	True	True	True	True	True
	tversky alpha	2.0000	1.2255	0.1388	0.0876	0.0000
	tversky beta	2.0000	2.0000	0.9260	0.6605	0.3728

Table 90. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Amazon Music original	Amazon Music ours	Amazon Movie	Movielens 100k	Movielens 1M
$P^3\alpha$	topK	871	453	1000	93	1000
	alpha	0.8151	0.4565	0.5195	0.0000	1.2781
	normalize similarity	True	True	False	True	False
$RP^3\beta$	topK	864	900	1000	311	405
	alpha	0.8665	0.9432	0.4285	0.3966	0.9764
	beta	0.1478	0.2462	0.2689	0.5232	0.5807
	normalize similarity	True	True	False	True	False
$EASE^R$	l2 norm	5.79E+03	-	-	1.66E+04	6.07E+04
SLIM BPR	topK	789	676	-	241	765
	epochs	175	255	-	260	345
	symmetric	True	True	-	True	True
	sgd mode	adam	adagrad	-	adagrad	adagrad
	lambda i	6.07E-04	2.02E-05	-	2.85E-03	1.00E-02
	lambda j	2.71E-03	5.73E-04	-	1.23E-04	1.00E-05
	learning rate	1.00E-01	7.89E-03	-	2.91E-02	4.12E-02
SLIMElasticNet	topK	1000	728	1000	96	694
	l1 ratio	8.28E-05	4.68E-05	4.41E-04	2.76E-03	1.86E-04
	alpha	1.0000	1.0000	1.0000	0.9354	0.6571
MF BPR	sgd mode	adagrad	adagrad	adagrad	adam	sgd
	epochs	420	495	1490	365	810
	num factors	183	200	200	200	200
	batch size	128	1	256	256	2
	positive reg	1.00E-02	1.00E-05	1.00E-02	1.00E-05	3.82E-05
	negative reg	1.00E-05	1.14E-03	1.00E-02	1.00E-05	1.00E-02
	learning rate	5.72E-02	7.38E-02	6.68E-02	2.36E-03	8.09E-02
MF FunkSVD	sgd mode	adam	sgd	adam	sgd	sgd
	epochs	450	230	245	130	400
	use bias	True	False	True	True	False
	batch size	16	2	32	8	1
	num factors	200	190	177	70	41
	item reg	3.33E-05	1.00E-02	2.69E-05	5.26E-04	2.21E-04
	user reg	1.00E-02	1.00E-02	1.00E-02	7.28E-03	1.54E-03
	learning rate	3.64E-04	2.43E-02	1.32E-03	1.48E-02	1.15E-03
	negative quota	0.0432	0.3709	0.0409	0.1257	0.1628
PureSVD	num factors	81	17	77	24	57
NMF	num factors	121	164	99	40	64
	solver	mult. update	mult. update	mult. update	coord. descent	coord. descent
	init type	random	random	nndsvda	nndsvda	nndsvda
	beta loss	frobenius	frobenius	kullback-leibler	frobenius	frobenius
iALS	num factors	31	28	52	25	63
	confidence scaling	log	log	log	log	log
	alpha	3.2850	50.0000	2.8548	0.0150	0.3345
	epsilon	0.0157	9.4295	0.0010	9.3913	0.0010
	reg	1.00E-02	1.00E-02	1.00E-05	1.00E-05	1.00E-05
	epochs	65	110	60	20	20

Table 91. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Amazon Music original	Amazon Music ours	Amazon Movie	Movielens 100k	Movielens 1M
DMF NCE	epochs	125	75	165	100	85
	learning rate	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
	batch size	256	256	256	256	256
	num negatives	7	7	7	7	7
	last layer size	128	128	64	64	64
	max rating	5.0000	5.0000	5.0000	5.0000	5.0000
DMF BCE	epochs	75	80	35	165	65
	learning rate	1.00E-04	1.00E-04	1.00E-04	1.00E-04	1.00E-04
	batch size	256	256	256	256	256
	num negatives	7	7	7	7	7
	last layer size	128	128	64	64	64
	max rating	1.0000	1.0000	1.0000	1.0000	1.0000

Table 92. Comparison of the computation time for the different algorithms.

	Amazon Music original		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	1.36 [sec]	621
TopPop	0.00 [sec]	1.53 [sec]	551
UserKNN CF cosine	0.05 ± 0.02 [sec]	2.28 ± 0.01 [sec]	368
UserKNN CF dice	0.05 ± 0.00 [sec]	2.26 ± 0.03 [sec]	378
UserKNN CF jaccard	0.05 ± 0.00 [sec]	2.27 ± 0.02 [sec]	376
UserKNN CF asymmetric	0.05 ± 0.00 [sec]	2.26 ± 0.04 [sec]	370
UserKNN CF tversky	0.05 ± 0.00 [sec]	2.27 ± 0.03 [sec]	380
ItemKNN CF cosine	3.33 ± 0.41 [sec]	2.36 ± 0.01 [sec]	357
ItemKNN CF dice	3.45 ± 0.15 [sec]	2.28 ± 0.01 [sec]	369
ItemKNN CF jaccard	3.46 ± 0.13 [sec]	2.31 ± 0.04 [sec]	360
ItemKNN CF asymmetric	3.55 ± 0.15 [sec]	2.32 ± 0.05 [sec]	358
ItemKNN CF tversky	3.53 ± 0.17 [sec]	2.29 ± 0.04 [sec]	370
$P^3\alpha$	14.26 ± 1.70 [sec]	2.31 ± 0.02 [sec]	363
$RP^3\beta$	14.36 ± 2.21 [sec]	2.30 ± 0.06 [sec]	362
$EASE^R$	125.05 [sec] / 2.08 ± 0.01 [min]	2.15 ± 0.01 [sec]	392
SLIM BPR	304.44 [sec] / 5.07 ± 2.50 [min]	2.18 ± 0.01 [sec]	387
SLIMElasticNet	410.27 [sec] / 6.84 ± 5.29 [min]	2.14 ± 0.03 [sec]	388
MF BPR	77.68 [sec] / 1.29 ± 0.90 [min]	1.58 ± 0.03 [sec]	527
MF FunkSVD	212.46 [sec] / 3.54 ± 3.48 [min]	1.65 ± 0.05 [sec]	497
PureSVD	0.39 ± 0.34 [sec]	1.60 ± 0.03 [sec]	532
NMF	50.60 ± 46.44 [sec]	1.77 ± 0.10 [sec]	508
iALS	441.76 [sec] / 7.36 ± 5.91 [min]	1.57 ± 0.01 [sec]	535
DMF normalized cross entropy	4355.24 [sec] / 1.21 [hour]	8.14 [sec]	104
DMF binary cross entropy	2902.64 [sec] / 48.38 [min]	8.04 [sec]	105

Table 93. Comparison of the computation time for the different algorithms.

	Amazon Music ours		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	1.29 [sec]	653
TopPop	0.00 [sec]	1.69 [sec]	498
UserKNN CF cosine	0.05 ± 0.00 [sec]	2.37 ± 0.01 [sec]	355
UserKNN CF dice	0.04 ± 0.00 [sec]	2.34 ± 0.02 [sec]	361
UserKNN CF jaccard	0.04 ± 0.00 [sec]	2.35 ± 0.01 [sec]	361
UserKNN CF asymmetric	0.04 ± 0.00 [sec]	2.36 ± 0.03 [sec]	354
UserKNN CF tversky	0.04 ± 0.00 [sec]	2.35 ± 0.03 [sec]	363
ItemKNN CF cosine	3.65 ± 0.65 [sec]	2.41 ± 0.03 [sec]	347
ItemKNN CF dice	4.01 ± 0.08 [sec]	2.40 ± 0.02 [sec]	351
ItemKNN CF jaccard	4.01 ± 0.06 [sec]	2.40 ± 0.01 [sec]	353
ItemKNN CF asymmetric	4.07 ± 0.09 [sec]	2.41 ± 0.01 [sec]	349
ItemKNN CF tversky	4.13 ± 0.07 [sec]	2.39 ± 0.05 [sec]	351
$P^3\alpha$	13.21 ± 0.96 [sec]	2.38 ± 0.02 [sec]	357
$RP^3\beta$	14.29 ± 1.10 [sec]	2.41 ± 0.02 [sec]	349
$EASE^R$	-	-	-
SLIM BPR	342.16 [sec] / 5.70 ± 3.42 [min]	2.41 ± 0.02 [sec]	347
SLIMElasticNet	1400.37 [sec] / 23.34 ± 2.14 [min]	2.43 ± 0.01 [sec]	345
MF BPR	90.35 [sec] / 1.51 ± 1.43 [min]	1.73 ± 0.02 [sec]	484
MF FunkSVD	146.22 [sec] / 2.44 ± 1.95 [min]	1.75 ± 0.01 [sec]	481
PureSVD	0.41 ± 0.48 [sec]	1.76 ± 0.07 [sec]	492
NMF	67.64 [sec] / 1.13 ± 0.96 [min]	1.91 ± 0.10 [sec]	453
iALS	184.95 [sec] / 3.08 ± 2.43 [min]	1.72 ± 0.00 [sec]	490
DMF normalized cross entropy	2071.19 [sec] / 34.52 [min]	8.38 [sec]	101
DMF binary cross entropy	2183.37 [sec] / 36.39 [min]	8.43 [sec]	100

Table 94. Comparison of the computation time for the different algorithms.

	Amazon Movie		
	Train time	Recommendation Time	[usr/s]
Random	0.03 [sec]	28.58 [sec]	527
TopPop	0.06 [sec]	43.04 [sec]	350
UserKNN CF cosine	4.67 ± 0.53 [sec]	63.92 [sec] / 1.07 ± 0.05 [min]	225
UserKNN CF dice	4.57 ± 0.52 [sec]	63.27 [sec] / 1.05 ± 0.06 [min]	228
UserKNN CF jaccard	4.59 ± 0.48 [sec]	64.06 [sec] / 1.07 ± 0.06 [min]	228
UserKNN CF asymmetric	4.72 ± 0.49 [sec]	66.17 [sec] / 1.10 ± 0.02 [min]	225
UserKNN CF tversky	4.63 ± 0.40 [sec]	63.04 [sec] / 1.05 ± 0.05 [min]	232
ItemKNN CF cosine	55.00 ± 5.26 [sec]	70.23 [sec] / 1.17 ± 0.08 [min]	203
ItemKNN CF dice	56.26 ± 1.87 [sec]	68.45 [sec] / 1.14 ± 0.08 [min]	216
ItemKNN CF jaccard	56.34 ± 1.87 [sec]	69.12 [sec] / 1.15 ± 0.05 [min]	226
ItemKNN CF asymmetric	56.82 ± 1.89 [sec]	71.95 [sec] / 1.20 ± 0.04 [min]	206
ItemKNN CF tversky	57.14 ± 2.12 [sec]	62.86 [sec] / 1.05 ± 0.05 [min]	239
$P^3\alpha$	196.62 [sec] / 3.28 ± 0.32 [min]	59.93 ± 1.25 [sec]	249
$RP^3\beta$	214.41 [sec] / 3.57 ± 0.31 [min]	60.62 [sec] / 1.01 ± 0.04 [min]	239
$EASE^R$	-	-	-
SLIM BPR	-	-	-
SLIMElasticNet	17335.50 [sec] / 4.82 ± 1.00 [hour]	64.46 [sec] / 1.07 ± 0.11 [min]	211
MF BPR	5985.66 [sec] / 1.66 ± 0.93 [hour]	43.42 ± 0.22 [sec]	345
MF FunkSVD	6606.42 [sec] / 1.84 ± 1.22 [hour]	47.53 ± 2.25 [sec]	309
PureSVD	4.39 ± 3.54 [sec]	45.12 ± 1.44 [sec]	343
NMF	2030.98 [sec] / 33.85 ± 20.16 [min]	45.26 [sec]	333
iALS	3384.98 [sec] / 56.42 ± 45.83 [min]	43.14 ± 0.15 [sec]	350
DMF normalized cross entropy	229915.93 [sec] / 2.66 [day]	385.76 [sec] / 6.43 [min]	39
DMF binary cross entropy	72580.90 [sec] / 20.16 [hour]	380.28 [sec] / 6.34 [min]	40

Table 95. Comparison of the computation time for the different algorithms.

	Movielens 100k		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	1.33 [sec]	706
TopPop	0.00 [sec]	1.39 [sec]	676
UserKNN CF cosine	0.14 ± 0.02 [sec]	2.09 ± 0.04 [sec]	448
UserKNN CF dice	0.14 ± 0.02 [sec]	2.13 ± 0.05 [sec]	449
UserKNN CF jaccard	0.15 ± 0.02 [sec]	2.13 ± 0.07 [sec]	454
UserKNN CF asymmetric	0.15 ± 0.02 [sec]	2.15 ± 0.08 [sec]	445
UserKNN CF tversky	0.15 ± 0.02 [sec]	2.09 ± 0.03 [sec]	452
ItemKNN CF cosine	0.20 ± 0.04 [sec]	2.14 ± 0.05 [sec]	429
ItemKNN CF dice	0.18 ± 0.04 [sec]	2.18 ± 0.11 [sec]	460
ItemKNN CF jaccard	0.19 ± 0.04 [sec]	2.16 ± 0.14 [sec]	458
ItemKNN CF asymmetric	0.20 ± 0.04 [sec]	2.20 ± 0.09 [sec]	454
ItemKNN CF tversky	0.18 ± 0.04 [sec]	2.14 ± 0.10 [sec]	454
$P^3\alpha$	0.99 ± 0.63 [sec]	2.08 ± 0.05 [sec]	460
$RP^3\beta$	1.21 ± 0.70 [sec]	2.12 ± 0.04 [sec]	446
$EASE^R$	0.41 ± 0.01 [sec]	1.88 ± 0.00 [sec]	500
SLIM BPR	64.02 [sec] / 1.07 ± 0.69 [min]	2.15 ± 0.07 [sec]	440
SLIMElasticNet	9.40 ± 4.87 [sec]	2.08 ± 0.01 [sec]	454
MF BPR	44.66 ± 46.61 [sec]	1.45 ± 0.04 [sec]	631
MF FunkSVD	156.60 [sec] / 2.61 ± 2.88 [min]	1.46 ± 0.01 [sec]	644
PureSVD	0.06 ± 0.05 [sec]	1.43 ± 0.01 [sec]	661
NMF	64.98 [sec] / 1.08 ± 1.03 [min]	1.45 ± 0.02 [sec]	646
iALS	39.52 ± 27.96 [sec]	1.44 ± 0.00 [sec]	655
DMF normalized cross entropy	15726.15 [sec] / 4.37 [hour]	22.78 [sec]	41
DMF binary cross entropy	23861.05 [sec] / 6.63 [hour]	22.85 [sec]	41

Table 96. Comparison of the computation time for the different algorithms.

	Movielens 1M		
	Train time	Recommendation Time	[usr/s]
Random	0.03 [sec]	8.68 [sec]	695
TopPop	0.05 [sec]	9.07 [sec]	665
UserKNN CF cosine	4.72 ± 0.25 [sec]	14.59 ± 1.40 [sec]	380
UserKNN CF dice	4.43 ± 0.21 [sec]	14.60 ± 0.55 [sec]	426
UserKNN CF jaccard	4.43 ± 0.22 [sec]	14.97 ± 0.70 [sec]	427
UserKNN CF asymmetric	4.51 ± 0.20 [sec]	15.31 ± 0.62 [sec]	388
UserKNN CF tversky	4.55 ± 0.22 [sec]	14.97 ± 0.36 [sec]	410
ItemKNN CF cosine	2.06 ± 0.11 [sec]	15.87 ± 1.14 [sec]	410
ItemKNN CF dice	2.02 ± 0.11 [sec]	14.59 ± 1.18 [sec]	437
ItemKNN CF jaccard	2.03 ± 0.11 [sec]	14.40 ± 0.66 [sec]	441
ItemKNN CF asymmetric	2.10 ± 0.11 [sec]	15.84 ± 1.07 [sec]	402
ItemKNN CF tversky	2.03 ± 0.13 [sec]	14.24 ± 0.36 [sec]	435
$P^3\alpha$	4.79 ± 1.34 [sec]	14.13 ± 0.30 [sec]	417
$RP^3\beta$	4.80 ± 1.32 [sec]	14.26 ± 0.51 [sec]	426
$EASE^R$	4.69 ± 0.02 [sec]	13.07 ± 0.18 [sec]	458
SLIM BPR	1067.49 [sec] / 17.79 ± 18.34 [min]	15.51 ± 0.33 [sec]	383
SLIMElasticNet	204.56 [sec] / 3.41 ± 3.33 [min]	14.18 ± 0.01 [sec]	425
MF BPR	450.68 [sec] / 7.51 ± 6.28 [min]	9.52 ± 0.12 [sec]	624
MF FunkSVD	2080.92 [sec] / 34.68 ± 26.08 [min]	9.49 ± 0.11 [sec]	638
PureSVD	0.83 ± 0.64 [sec]	9.56 ± 0.11 [sec]	635
NMF	355.21 [sec] / 5.92 ± 13.25 [min]	9.56 ± 0.02 [sec]	630
iALS	273.69 [sec] / 4.56 ± 2.68 [min]	9.52 ± 0.02 [sec]	631
DMF normalized cross entropy	428434.48 [sec] / 4.96 [day]	480.79 [sec] / 8.01 [min]	13
DMF binary cross entropy	351928.51 [sec] / 4.07 [day]	482.96 [sec] / 8.05 [min]	12

M IJCAI: COUPLEDCF: LEARNING EXPLICIT AND IMPLICIT USER-ITEM COUPLINGS IN RECOMMENDATION FOR DEEP COLLABORATIVE FILTERING

Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 97. The results of our evaluation can be seen in Table 98 (Movielens 1M) and Table 99 (Tafeng). The corresponding optimal hyperparameters are reported in Table 100 (collaborative KNNs), Table 101 (non-neural machine learning and graph based), Table 102 (content-based KNNs), Table 103 (hybrid KNNs item-based), Table 104 (hybrid KNNs user-based) and Table 105 (CoupledCF).

Lastly, the time required to train and evaluate the models is reported in Table 106 (Movielens 1M) and Table 107 (Tafeng).

Table 97. Dataset characteristics.

Dataset	Interactions	Items	Users	Density
Movielens 1M	1M	3953	6041	4.18
Tafeng	743K	23813	32267	0.097

Table 98. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 1M					
	@1		@5		@10	
	HR	NDCG	HR	NDCG	HR	NDCG
Random	0.0104	0.0104	0.0493	0.0290	0.0972	0.0443
TopPop	0.1084	0.1084	0.3224	0.2174	0.4740	0.2661
UserKNN CF cosine	0.1985	0.1985	0.5189	0.3653	0.6808	0.4178
UserKNN CF dice	0.1962	0.1962	0.5167	0.3631	0.6714	0.4133
UserKNN CF jaccard	0.1947	0.1947	0.5187	0.3633	0.6748	0.4139
UserKNN CF asymmetric	0.2000	0.2000	0.5220	0.3677	0.6896	0.4220
UserKNN CF tversky	0.1972	0.1972	0.5194	0.3649	0.6781	0.4165
ItemKNN CF cosine	0.1810	0.1810	0.5111	0.3514	0.6844	0.4077
ItemKNN CF dice	0.1818	0.1818	0.5038	0.3468	0.6775	0.4031
ItemKNN CF jaccard	0.1765	0.1765	0.5003	0.3434	0.6738	0.3996
ItemKNN CF asymmetric	0.1783	0.1783	0.4781	0.3321	0.6478	0.3872
ItemKNN CF tversky	0.1800	0.1800	0.5000	0.3436	0.6659	0.3975
P3alpha	0.1829	0.1829	0.4965	0.3451	0.6589	0.3978
RP3beta	0.1801	0.1801	0.5083	0.3498	0.6623	0.3996
EASE R	**0.2187**	**0.2187**	**0.5675**	**0.3988**	**0.7260**	**0.4502**
SLIM BPR	0.2070	0.2070	0.5363	0.3769	0.6990	0.4297
SLIMElasticNet	**0.2258**	**0.2258**	**0.5778**	**0.4073**	**0.7281**	**0.4561**
MF BPR	0.1806	0.1806	0.4985	0.3437	0.6662	0.3981
MF FunkSVD	0.2051	0.2051	0.5368	0.3771	0.6944	0.4284
PureSVD	**0.2167**	**0.2167**	**0.5540**	**0.3916**	0.7055	**0.4408**
NMF	0.2000	0.2000	0.5334	0.3723	0.6861	0.4217
IALS	**0.2220**	**0.2220**	**0.5680**	**0.4015**	**0.7225**	**0.4516**
ItemKNN CBF cosine	0.0652	0.0652	0.2167	0.1414	0.3364	0.1800
ItemKNN CBF dice	0.0598	0.0598	0.2030	0.1321	0.3185	0.1692
ItemKNN CBF jaccard	0.0606	0.0606	0.2017	0.1321	0.3164	0.1690
ItemKNN CBF asymmetric	0.0636	0.0636	0.2164	0.1412	0.3406	0.1812
ItemKNN CBF tversky	0.0596	0.0596	0.2026	0.1320	0.3192	0.1693
UserKNN CBF cosine	0.1182	0.1182	0.3373	0.2291	0.4990	0.2813
UserKNN CBF dice	0.1175	0.1175	0.3371	0.2288	0.4982	0.2807
UserKNN CBF jaccard	0.1192	0.1192	0.3377	0.2295	0.5010	0.2820
UserKNN CBF asymmetric	0.1177	0.1177	0.3374	0.2289	0.4980	0.2806
UserKNN CBF tversky	0.1200	0.1200	0.3381	0.2300	0.5013	0.2826
ItemKNN CFCBF cosine	0.1818	0.1818	0.5159	0.3526	0.6833	0.4068
ItemKNN CFCBF dice	0.1813	0.1813	0.5022	0.3465	0.6770	0.4032
ItemKNN CFCBF jaccard	0.1791	0.1791	0.4997	0.3433	0.6707	0.3988
ItemKNN CFCBF asymmetric	0.1820	0.1820	0.5048	0.3477	0.6732	0.4023
ItemKNN CFCBF tversky	0.1765	0.1765	0.4768	0.3309	0.6536	0.3882
UserKNN CFCBF cosine	0.1889	0.1889	0.5154	0.3572	0.6790	0.4102
UserKNN CFCBF dice	0.1993	0.1993	0.5175	0.3649	0.6805	0.4177
UserKNN CFCBF jaccard	0.1983	0.1983	0.5171	0.3645	0.6803	0.4175
UserKNN CFCBF asymmetric	0.1892	0.1892	0.5144	0.3555	0.6820	0.4099
UserKNN CFCBF tversky	0.1967	0.1967	0.5182	0.3641	0.6877	0.4193
DeepCF	0.1959	0.1959	0.5522	0.3795	0.7171	0.4330
CoupledCF	0.2071	0.2071	0.5465	0.3817	0.7079	0.4342

Table 99. Experimental results on the metrics and cutoffs reported in the original paper.

	Tafeng					
	@1		@5		@10	
	HR	NDCG	HR	NDCG	HR	NDCG
Random	0.0551	0.0551	0.0936	0.0737	0.1389	0.0881
TopPop	0.2809	0.2809	0.5287	0.4094	0.6614	0.4523
UserKNN CF cosine	**0.3498**	**0.3498**	**0.5737**	**0.4674**	**0.6703**	**0.4987**
UserKNN CF dice	**0.3477**	**0.3477**	**0.5680**	**0.4632**	**0.6661**	**0.4950**
UserKNN CF jaccard	**0.3473**	**0.3473**	**0.5678**	**0.4629**	**0.6659**	**0.4946**
UserKNN CF asymmetric	**0.3487**	**0.3487**	**0.5717**	**0.4657**	**0.6686**	**0.4971**
UserKNN CF tversky	**0.3472**	**0.3472**	**0.5679**	**0.4628**	**0.6658**	**0.4946**
ItemKNN CF cosine	**0.3573**	**0.3573**	**0.5727**	**0.4709**	**0.6648**	**0.5007**
ItemKNN CF dice	**0.3458**	**0.3458**	**0.5773**	**0.4673**	**0.6770**	**0.4996**
ItemKNN CF jaccard	**0.3484**	**0.3484**	**0.5766**	**0.4680**	**0.6717**	**0.4989**
ItemKNN CF asymmetric	**0.3615**	**0.3615**	**0.5726**	**0.4733**	0.6541	**0.4997**
ItemKNN CF tversky	**0.3516**	**0.3516**	**0.5788**	**0.4713**	**0.6647**	**0.4992**
P3alpha	**0.3523**	**0.3523**	**0.5844**	**0.4749**	**0.6775**	**0.5051**
RP3beta	**0.3400**	**0.3400**	0.5140	**0.4322**	0.5898	0.4567
EASE R	**0.3503**	**0.3503**	**0.5719**	**0.4666**	**0.6696**	**0.4982**
SLIM BPR	**0.3500**	**0.3500**	**0.5792**	**0.4705**	**0.6723**	**0.5006**
SLIMElasticNet	**0.3496**	**0.3496**	**0.5721**	**0.4666**	**0.6724**	**0.4991**
MF BPR	0.2413	0.2413	0.4641	0.3562	0.5808	0.3939
MF FunkSVD	0.2853	0.2853	0.5300	0.4123	0.6614	0.4548
PureSVD	0.2751	0.2751	0.5222	0.4032	0.6535	0.4457
NMF	0.2476	0.2476	0.4603	0.3584	0.5769	0.3961
IALS	**0.3296**	**0.3296**	**0.5634**	**0.4530**	0.6621	**0.4849**
ItemKNN CBF cosine	0.0545	0.0545	0.0905	0.0722	0.1342	0.0861
ItemKNN CBF dice	0.0537	0.0537	0.0916	0.0723	0.1350	0.0861
ItemKNN CBF jaccard	0.0537	0.0537	0.0917	0.0723	0.1354	0.0862
ItemKNN CBF asymmetric	0.0547	0.0547	0.0946	0.0741	0.1425	0.0894
ItemKNN CBF tversky	0.0537	0.0537	0.0918	0.0723	0.1353	0.0862
UserKNN CBF cosine	0.2604	0.2604	0.4728	0.3705	0.5831	0.4061
UserKNN CBF dice	0.2562	0.2562	0.4635	0.3640	0.5701	0.3984
UserKNN CBF jaccard	0.2559	0.2559	0.4631	0.3636	0.5692	0.3978
UserKNN CBF asymmetric	0.2632	0.2632	0.4768	0.3743	0.5885	0.4103
UserKNN CBF tversky	0.2564	0.2564	0.4643	0.3644	0.5708	0.3988
ItemKNN CFCBF cosine	**0.3573**	**0.3573**	**0.5727**	**0.4709**	**0.6650**	**0.5008**
ItemKNN CFCBF dice	**0.3329**	**0.3329**	**0.5642**	**0.4541**	**0.6677**	**0.4878**
ItemKNN CFCBF jaccard	**0.3348**	**0.3348**	**0.5669**	**0.4562**	**0.6646**	**0.4879**
ItemKNN CFCBF asymmetric	**0.3611**	**0.3611**	**0.5735**	**0.4736**	0.6561	**0.5003**
ItemKNN CFCBF tversky	**0.3357**	**0.3357**	**0.5675**	**0.4573**	**0.6651**	**0.4890**
UserKNN CFCBF cosine	**0.3536**	**0.3536**	**0.5858**	**0.4766**	**0.6874**	**0.5095**
UserKNN CFCBF dice	**0.3289**	**0.3289**	**0.5576**	**0.4490**	0.6594	**0.4819**
UserKNN CFCBF jaccard	**0.3272**	**0.3272**	**0.5551**	**0.4469**	0.6570	**0.4799**
UserKNN CFCBF asymmetric	**0.3584**	**0.3584**	**0.5915**	**0.4814**	**0.6907**	**0.5136**
UserKNN CFCBF tversky	**0.3259**	**0.3259**	**0.5529**	**0.4451**	0.6554	**0.4782**
DeepCF	0.2869	0.2869	0.5366	0.4169	0.6637	0.4581
CoupledCF	0.2767	0.2767	0.5272	0.4065	0.6597	0.4494

Table 100. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Tafeng
UserKNN CF cosine	topK	363	1000
	shrink	0	327
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	TF-IDF	TF-IDF
UserKNN CF dice	topK	165	1000
	shrink	0	0
	similarity	dice	dice
	normalize	True	True
UserKNN CF jaccard	topK	187	1000
	shrink	0	0
	similarity	jaccard	jaccard
	normalize	False	False
UserKNN CF asymmetric	topK	268	1000
	shrink	212	82
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.0000	0.4272
	feature weighting	TF-IDF	TF-IDF
UserKNN CF tversky	topK	221	1000
	shrink	0	0
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	1.5095	2.0000
	tversky beta	2.0000	2.0000
ItemKNN CF cosine	topK	66	1000
	shrink	302	1000
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	TF-IDF	TF-IDF
ItemKNN CF dice	topK	50	995
	shrink	5	65
	similarity	dice	dice
	normalize	False	True
ItemKNN CF jaccard	topK	43	999
	shrink	2	35
	similarity	jaccard	jaccard
	normalize	True	False
ItemKNN CF asymmetric	topK	446	1000
	shrink	906	975
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.9254	0.3635
	feature weighting	BM25	TF-IDF
ItemKNN CF tversky	topK	42	784
	shrink	298	100
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.0000	0.9383
	tversky beta	0.9369	1.9574

Table 101. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Tafeng
$P^3\alpha$	topK	342	1000
	alpha	1.5568	0.5325
	normalize similarity	True	False
$RP^3\beta$	topK	200	1000
	alpha	1.2485	0.4449
	beta	0.2230	0.3373
	normalize similarity	True	True
$EASE^R$	l2 norm	2.94E+03	4.21E+03
SLIM BPR	topK	1000	808
	epochs	270	425
	symmetric	True	False
	sgd mode	sgd	adagrad
	lambda i	1.00E-02	1.00E-05
	lambda j	1.00E-05	1.00E-02
	learning rate	4.31E-03	1.00E-04
SLIMElasticNet	topK	453	841
	l1 ratio	9.77E-04	7.24E-05
	alpha	0.0564	0.1668
MF BPR	sgd mode	sgd	sgd
	epochs	1005	420
	num factors	131	1
	batch size	2	4
	positive reg	1.00E-05	1.00E-05
	negative reg	1.00E-02	1.00E-02
	learning rate	7.63E-02	6.60E-02
MF FunkSVD	sgd mode	adam	adam
	epochs	260	40
	use bias	True	True
	batch size	256	32
	num factors	44	1
	item reg	7.79E-04	4.54E-04
	user reg	2.90E-05	1.49E-03
	learning rate	5.26E-04	1.00E-04
	negative quota	0.0672	0.5000
PureSVD	num factors	65	1
NMF	num factors	112	44
	solver	mult. update	coord. descent
	init type	random	random
	beta loss	kullback-leibler	frobenius
iALS	num factors	78	26
	confidence scaling	linear	linear
	alpha	1.7666	16.1876
	epsilon	10.0000	0.1320
	reg	1.00E-05	1.22E-05
	epochs	40	40

Table 102. Hyperparameter values for our hybrid KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Tafeng
ItemKNN CBF cosine	topK	1000	561
	shrink	1000	528
	similarity	cosine	cosine
	normalize	True	False
	feature weighting	TF-IDF	none
ItemKNN CBF dice	topK	318	636
	shrink	323	369
	similarity	dice	dice
	normalize	False	True
ItemKNN CBF jaccard	topK	283	991
	shrink	553	998
	similarity	jaccard	jaccard
	normalize	False	False
ItemKNN CBF asymmetric	topK	986	500
	shrink	785	545
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	2.0000	0.4976
	feature weighting	TF-IDF	none
ItemKNN CBF tversky	topK	322	980
	shrink	354	12
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.8065	0.0031
	tversky beta	0.1989	1.8880
UserKNN CBF cosine	topK	801	1000
	shrink	1000	0
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	none	BM25
UserKNN CBF dice	topK	787	999
	shrink	10	959
	similarity	dice	dice
	normalize	False	True
UserKNN CBF jaccard	topK	793	999
	shrink	0	41
	similarity	jaccard	jaccard
	normalize	False	False
UserKNN CBF asymmetric	topK	788	1000
	shrink	992	510
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.0306	0.0000
	feature weighting	none	TF-IDF
UserKNN CBF tversky	topK	1000	1000
	shrink	0	1000
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	2.0000	0.0000
	tversky beta	2.0000	0.0000

Table 103. Hyperparameter values for our baselines on all reported algorithms and datasets.

Algorithm	Hyperparameter	Movielens 1M	Tafeng
ItemKNN CFCBF cosine	topK	168	1000
	shrink	875	1000
	similarity	cosine	cosine
	normalize	False	True
	feature weighting	BM25	TF-IDF
	ICM weight	1.6619	9.1735
ItemKNN CFCBF dice	topK	49	890
	shrink	0	434
	similarity	dice	dice
	normalize	True	True
	ICM weight	94.1764	100.0000
ItemKNN CFCBF jaccard	topK	55	830
	shrink	0	363
	similarity	jaccard	jaccard
	normalize	False	False
	ICM weight	100.0000	0.0100
ItemKNN CFCBF asymmetric	topK	231	1000
	shrink	1000	1000
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.5629	0.3744
	feature weighting	BM25	TF-IDF
	ICM weight	0.2198	0.0100
ItemKNN CFCBF tversky	topK	46	882
	shrink	874	684
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.2974	1.2102
	tversky beta	0.6227	1.9959
	ICM weight	0.6018	4.6249

Table 104. Hyperparameter values for our hybrid KNN baselines on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Tafeng
UserKNN CFCBF cosine	topK	263	683
	shrink	0	510
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	BM25	BM25
	UCM weight	0.0262	4.9570
UserKNN CFCBF dice	topK	202	997
	shrink	1	18
	similarity	dice	dice
	normalize	False	True
	UCM weight	2.5156	0.0115
UserKNN CFCBF jaccard	topK	190	993
	shrink	2	5
	similarity	jaccard	jaccard
	normalize	True	True
	UCM weight	0.8025	43.6604
UserKNN CFCBF asymmetric	topK	350	670
	shrink	0	451
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.0000	0.7234
	feature weighting	BM25	BM25
	UCM weight	0.0100	2.5995
UserKNN CFCBF tversky	topK	224	1000
	shrink	0	0
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.8562	1.5529
	tversky beta	1.7705	1.8388
	UCM weight	0.0100	100.0000

Table 105. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Movielens 1M	Tafeng
DeepCF	learning rate	1.00E-03	5.00E-03
	epochs	15	15
	n negative sample	4	4
CoupledCF	learning rate	1.00E-03	5.00E-03
	epochs	40	5
	n negative sample	4	4

Table 106. Comparison of the computation time for the different algorithms.

	Movielens 1M		
	Train time	Recommendation Time	[usr/s]
Random	0.02 [sec]	10.19 [sec]	593
TopPop	0.03 [sec]	11.38 [sec]	531
UserKNN CF cosine	3.14 ± 0.17 [sec]	15.78 ± 0.38 [sec]	386
UserKNN CF dice	3.03 ± 0.15 [sec]	15.60 ± 0.64 [sec]	403
UserKNN CF jaccard	3.04 ± 0.16 [sec]	15.73 ± 0.59 [sec]	396
UserKNN CF asymmetric	3.12 ± 0.18 [sec]	15.73 ± 0.71 [sec]	393
UserKNN CF tversky	3.15 ± 0.17 [sec]	16.03 ± 0.70 [sec]	395
ItemKNN CF cosine	1.48 ± 0.10 [sec]	16.46 ± 1.46 [sec]	400
ItemKNN CF dice	1.45 ± 0.08 [sec]	15.43 ± 1.18 [sec]	410
ItemKNN CF jaccard	1.45 ± 0.08 [sec]	15.15 ± 0.60 [sec]	416
ItemKNN CF asymmetric	1.56 ± 0.10 [sec]	16.67 ± 0.60 [sec]	362
ItemKNN CF tversky	1.41 ± 0.08 [sec]	15.77 ± 1.39 [sec]	412
$P^3\alpha$	3.23 ± 0.85 [sec]	14.91 ± 0.21 [sec]	409
$RP^3\beta$	3.35 ± 1.07 [sec]	14.94 ± 0.33 [sec]	413
$EASE^R$	4.04 ± 0.02 [sec]	14.85 ± 0.20 [sec]	404
SLIM BPR	721.91 [sec] / 12.03 ± 9.52 [min]	16.28 ± 0.45 [sec]	362
SLIMElasticNet	171.44 [sec] / 2.86 ± 1.86 [min]	14.69 ± 0.73 [sec]	402
MF BPR	471.61 [sec] / 7.86 ± 5.82 [min]	16.58 ± 2.70 [sec]	332
MF FunkSVD	1860.97 [sec] / 31.02 ± 34.81 [min]	14.78 ± 2.96 [sec]	479
PureSVD	0.82 ± 0.46 [sec]	13.42 ± 2.36 [sec]	484
NMF	547.17 [sec] / 9.12 ± 6.08 [min]	17.01 ± 2.98 [sec]	330
iALS	464.07 [sec] / 7.73 ± 4.84 [min]	12.50 ± 0.11 [sec]	479
ItemKNN CBF cosine	0.27 ± 0.06 [sec]	14.85 ± 0.60 [sec]	396
ItemKNN CBF dice	0.26 ± 0.05 [sec]	14.41 ± 0.12 [sec]	423
ItemKNN CBF jaccard	0.27 ± 0.05 [sec]	14.19 ± 0.30 [sec]	421
ItemKNN CBF asymmetric	0.29 ± 0.06 [sec]	15.42 ± 0.35 [sec]	384
ItemKNN CBF tversky	0.26 ± 0.05 [sec]	14.26 ± 0.40 [sec]	418
UserKNN CBF cosine	0.71 ± 0.06 [sec]	17.62 ± 0.55 [sec]	340
UserKNN CBF dice	0.75 ± 0.09 [sec]	17.88 ± 0.24 [sec]	341
UserKNN CBF jaccard	0.77 ± 0.09 [sec]	17.59 ± 0.35 [sec]	343
UserKNN CBF asymmetric	0.78 ± 0.12 [sec]	17.95 ± 0.25 [sec]	339
UserKNN CBF tversky	0.76 ± 0.09 [sec]	17.83 ± 0.36 [sec]	332
ItemKNN CFCBF cosine	1.48 ± 0.09 [sec]	16.26 ± 0.84 [sec]	395
ItemKNN CFCBF dice	1.48 ± 0.09 [sec]	14.60 ± 0.58 [sec]	423
ItemKNN CFCBF jaccard	1.48 ± 0.08 [sec]	14.50 ± 0.13 [sec]	422
ItemKNN CFCBF asymmetric	1.54 ± 0.08 [sec]	15.55 ± 0.31 [sec]	390
ItemKNN CFCBF tversky	1.47 ± 0.09 [sec]	15.28 ± 1.47 [sec]	414
UserKNN CFCBF cosine	3.10 ± 0.13 [sec]	17.10 ± 0.61 [sec]	365
UserKNN CFCBF dice	3.11 ± 0.17 [sec]	17.11 ± 0.42 [sec]	349
UserKNN CFCBF jaccard	3.07 ± 0.18 [sec]	16.83 ± 0.64 [sec]	371
UserKNN CFCBF asymmetric	3.26 ± 0.29 [sec]	17.50 ± 0.74 [sec]	361
UserKNN CFCBF tversky	3.23 ± 0.25 [sec]	16.82 ± 0.66 [sec]	368
DeepCF	3901.52 [sec] / 1.08 [hour]	25.05 [sec]	241
CoupledCF	14029.82 [sec] / 3.90 [hour]	34.18 [sec]	177

Table 107. Comparison of the computation time for the different algorithms.

	Tafeng		
	Train time	Recommendation Time	[usr/s]
Random	0.01 [sec]	57.31 [sec]	536
TopPop	0.02 [sec]	63.39 [sec] / 1.06 [min]	485
UserKNN CF cosine	10.08 ± 0.90 [sec]	82.01 [sec] / 1.37 ± 0.07 [min]	358
UserKNN CF dice	10.34 ± 0.66 [sec]	82.74 [sec] / 1.38 ± 0.07 [min]	360
UserKNN CF jaccard	10.45 ± 0.65 [sec]	84.58 [sec] / 1.41 ± 0.01 [min]	361
UserKNN CF asymmetric	10.24 ± 0.80 [sec]	82.03 [sec] / 1.37 ± 0.04 [min]	360
UserKNN CF tversky	10.45 ± 0.78 [sec]	81.36 [sec] / 1.36 ± 0.07 [min]	357
ItemKNN CF cosine	4.28 ± 0.35 [sec]	84.92 [sec] / 1.42 ± 0.05 [min]	354
ItemKNN CF dice	4.34 ± 0.27 [sec]	85.91 [sec] / 1.43 ± 0.01 [min]	359
ItemKNN CF jaccard	4.37 ± 0.30 [sec]	83.91 [sec] / 1.40 ± 0.09 [min]	358
ItemKNN CF asymmetric	4.46 ± 0.31 [sec]	82.72 [sec] / 1.38 ± 0.11 [min]	358
ItemKNN CF tversky	4.21 ± 0.31 [sec]	85.76 [sec] / 1.43 ± 0.01 [min]	362
$P^3\alpha$	16.15 ± 3.44 [sec]	77.19 [sec] / 1.29 ± 0.05 [min]	384
$RP^3\beta$	19.20 ± 3.05 [sec]	78.05 [sec] / 1.30 ± 0.03 [min]	387
$EASE^R$	310.60 [sec] / 5.18 ± 0.07 [min]	75.08 [sec] / 1.25 ± 0.05 [min]	418
SLIM BPR	2499.23 [sec] / 41.65 ± 18.16 [min]	78.52 [sec] / 1.31 ± 0.01 [min]	392
SLIMElasticNet	527.87 [sec] / 8.80 ± 4.22 [min]	80.33 [sec] / 1.34 ± 0.08 [min]	360
MF BPR	1856.56 [sec] / 30.94 ± 28.65 [min]	69.71 [sec] / 1.16 ± 0.19 [min]	476
MF FunkSVD	1721.76 [sec] / 28.70 ± 36.20 [min]	73.04 [sec] / 1.22 ± 0.20 [min]	460
PureSVD	1.19 ± 1.72 [sec]	63.30 [sec] / 1.06 ± 0.02 [min]	481
NMF	396.04 [sec] / 6.60 ± 3.69 [min]	75.72 [sec] / 1.26 ± 0.29 [min]	473
iALS	1870.58 [sec] / 31.18 ± 27.80 [min]	65.58 [sec] / 1.09 ± 0.00 [min]	469
ItemKNN CBF cosine	13.56 ± 7.13 [sec]	68.00 [sec] / 1.13 ± 0.01 [min]	451
ItemKNN CBF dice	12.10 ± 6.57 [sec]	66.94 [sec] / 1.12 ± 0.01 [min]	461
ItemKNN CBF jaccard	13.21 ± 6.67 [sec]	67.27 [sec] / 1.12 ± 0.01 [min]	453
ItemKNN CBF asymmetric	13.24 ± 6.89 [sec]	68.53 [sec] / 1.14 ± 0.04 [min]	437
ItemKNN CBF tversky	15.57 ± 6.33 [sec]	68.15 [sec] / 1.14 ± 0.01 [min]	447
UserKNN CBF cosine	12.43 ± 1.13 [sec]	87.55 [sec] / 1.46 ± 0.07 [min]	340
UserKNN CBF dice	12.35 ± 0.65 [sec]	89.77 [sec] / 1.50 ± 0.02 [min]	339
UserKNN CBF jaccard	12.95 ± 0.88 [sec]	90.25 [sec] / 1.50 ± 0.04 [min]	336
UserKNN CBF asymmetric	13.36 ± 0.86 [sec]	91.22 [sec] / 1.52 ± 0.02 [min]	339
UserKNN CBF tversky	13.02 ± 0.82 [sec]	90.31 [sec] / 1.51 ± 0.10 [min]	341
ItemKNN CFCBF cosine	13.59 ± 1.28 [sec]	81.15 [sec] / 1.35 ± 0.03 [min]	372
ItemKNN CFCBF dice	13.71 ± 0.60 [sec]	77.25 [sec] / 1.29 ± 0.03 [min]	393
ItemKNN CFCBF jaccard	13.67 ± 0.64 [sec]	77.42 [sec] / 1.29 ± 0.02 [min]	398
ItemKNN CFCBF asymmetric	14.24 ± 0.90 [sec]	79.89 [sec] / 1.33 ± 0.08 [min]	375
ItemKNN CFCBF tversky	13.20 ± 1.08 [sec]	76.06 [sec] / 1.27 ± 0.04 [min]	398
UserKNN CFCBF cosine	15.01 ± 0.56 [sec]	89.86 [sec] / 1.50 ± 0.02 [min]	345
UserKNN CFCBF dice	16.99 ± 0.92 [sec]	94.92 [sec] / 1.58 ± 0.09 [min]	336
UserKNN CFCBF jaccard	16.73 ± 1.06 [sec]	92.12 [sec] / 1.54 ± 0.06 [min]	309
UserKNN CFCBF asymmetric	16.42 ± 1.22 [sec]	90.62 [sec] / 1.51 ± 0.01 [min]	340
UserKNN CFCBF tversky	16.78 ± 1.19 [sec]	92.53 [sec] / 1.54 ± 0.09 [min]	340
DeepCF	3182.28 [sec] / 53.04 [min]	131.53 [sec] / 2.19 [min]	234
CoupledCF	4632.16 [sec] / 1.29 [hour]	198.59 [sec] / 3.31 [min]	155

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Relevant statistics on the dataset, which we mentioned in the paper, are reported in Table 108. The results of our evaluation can be seen in Table 109 (Amazon Music) and Table 110 (Movielens 1M). The corresponding optimal hyperparameters are reported in Table 111 (collaborative KNNs), Table 112 (non-neural machine learning and graph based) and Table 113 (DELF).

Lastly, the time required to train and evaluate the models is reported in Table 114 (Amazon Music) and Table 115 (Movielens 1M).

Table 108. Dataset characteristics.

Dataset		Interactions	Items	Users	Density
Amazon Music	original	836K	266414	478235	$6.56 \cdot 10^{-4}$
Amazon Music	preprocessed	76K	41488	1835	0.100
Movielens 1M	-	1M	3706	6040	4.468

Table 109. Experimental results on the metrics and cutoffs reported in the original paper.

	Amazon Music					
	@5		@10		@20	
	HR	NDCG	HR	NDCG	HR	NDCG
Random	0.0567	0.0353	0.1079	0.0516	0.2174	0.0789
TopPop	0.2474	0.1730	0.3041	0.1913	0.3738	0.2090
UserKNN CF cosine	**0.3150**	**0.2495**	**0.3471**	**0.2600**	0.3738	**0.2668**
UserKNN CF dice	**0.3106**	**0.2470**	**0.3471**	**0.2590**	0.3744	**0.2659**
UserKNN CF jaccard	**0.3106**	**0.2474**	**0.3471**	**0.2594**	0.3738	**0.2663**
UserKNN CF asymmetric	**0.3084**	**0.2464**	**0.3460**	**0.2587**	0.3744	**0.2660**
UserKNN CF tversky	**0.3117**	**0.2475**	**0.3471**	**0.2591**	0.3744	**0.2661**
ItemKNN CF cosine	**0.3084**	**0.2464**	**0.3428**	**0.2576**	0.3744	**0.2655**
ItemKNN CF dice	**0.3025**	**0.2389**	**0.3422**	**0.2517**	0.3744	**0.2598**
ItemKNN CF jaccard	**0.2992**	**0.2382**	0.3324	**0.2489**	0.3575	**0.2552**
ItemKNN CF asymmetric	**0.3090**	**0.2506**	**0.3401**	**0.2609**	0.3717	**0.2689**
ItemKNN CF tversky	**0.2965**	**0.2380**	0.3319	**0.2495**	0.3591	**0.2564**
$P^3\alpha$	**0.3074**	**0.2465**	**0.3373**	**0.2564**	0.3689	**0.2644**
$RP^3\beta$	**0.3046**	**0.2434**	**0.3379**	**0.2543**	0.3651	**0.2611**
$EASE^R$	-	-	-	-	-	-
SLIM BPR	**0.3008**	**0.2380**	**0.3390**	**0.2504**	0.3673	**0.2576**
SLIMElasticNet	**0.3101**	**0.2526**	**0.3411**	**0.2625**	0.3711	**0.2701**
MF BPR	0.2360	0.1888	0.2687	0.1995	0.3095	0.2099
MF FunkSVD	0.2545	0.2035	0.2899	0.2150	0.3292	0.2248
PureSVD	0.2627	0.2141	0.3084	0.2290	0.3542	0.2406
NMF	**0.2910**	**0.2294**	**0.3482**	**0.2480**	**0.4038**	**0.2621**
iALS	**0.3319**	**0.2604**	**0.3706**	**0.2729**	**0.4109**	**0.2831**
DELF MLP	0.2883	0.2239	0.3335	0.2386	0.3760	0.2494
DELF EF	0.2856	0.2159	0.3330	0.2315	0.3809	0.2437

Table 110. Experimental results on the metrics and cutoffs reported in the original paper.

	Movielens 1M					
	@5		@10		@20	
	HR	NDCG	HR	NDCG	HR	NDCG
Random	0.0533	0.0320	0.1042	0.0481	0.2024	0.0726
TopPop	0.3300	0.2228	0.4698	0.2674	0.6576	0.3148
UserKNN CF cosine	0.5193	**0.3621**	0.6837	**0.4155**	0.8263	**0.4516**
UserKNN CF dice	0.5147	**0.3608**	0.6791	**0.4142**	0.8218	**0.4505**
UserKNN CF jaccard	0.5163	**0.3620**	0.6783	**0.4145**	0.8230	**0.4512**
UserKNN CF asymmetric	0.5188	**0.3628**	0.6865	**0.4171**	0.8334	**0.4544**
UserKNN CF tversky	0.5158	**0.3617**	0.6748	**0.4135**	0.8253	**0.4515**
ItemKNN CF cosine	0.4978	0.3418	0.6814	0.4011	0.8311	0.4390
ItemKNN CF dice	0.4895	0.3370	0.6667	0.3943	0.8276	0.4352
ItemKNN CF jaccard	0.4958	0.3408	0.6723	0.3978	0.8202	0.4355
ItemKNN CF asymmetric	0.5011	0.3452	0.6789	0.4027	0.8286	0.4407
ItemKNN CF tversky	0.4936	0.3418	0.6615	0.3963	0.8036	0.4323
$P^3\alpha$	0.4945	0.3438	0.6574	0.3965	0.7950	0.4313
$RP^3\beta$	0.5138	0.3559	0.6809	0.4102	0.8276	0.4475
$EASE^R$	**0.5609**	**0.3954**	**0.7248**	**0.4486**	**0.8559**	**0.4818**
SLIM BPR	**0.5380**	**0.3742**	**0.7077**	**0.4292**	**0.8452**	**0.4640**
SLIMElasticNet	**0.5706**	**0.4038**	**0.7306**	**0.4557**	**0.8586**	**0.4882**
MF BPR	0.4844	0.3310	0.6595	0.3877	0.8152	0.4275
MF FunkSVD	**0.5312**	**0.3708**	**0.6948**	**0.4239**	0.8245	**0.4569**
PureSVD	**0.5513**	**0.3891**	**0.7021**	**0.4382**	0.8303	**0.4708**
NMF	**0.5339**	**0.3746**	**0.6965**	**0.4272**	**0.8385**	**0.4635**
iALS	**0.5652**	**0.3979**	**0.7268**	**0.4503**	**0.8465**	**0.4807**
DELF MLP	0.5234	0.3592	0.6892	0.4132	0.8356	0.4503
DELF EF	0.4718	0.3210	0.6423	0.3762	0.7942	0.4146

Table 111. Hyperparameter values for our collaborative KNN baselines on all datasets.

Algorithm	Hyperparameter	Amazon Music	Movielens 1M
UserKNN CF cosine	topK	1000	461
	shrink	0	0
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	none	TF-IDF
UserKNN CF dice	topK	916	339
	shrink	9	0
	similarity	dice	dice
	normalize	False	True
UserKNN CF jaccard	topK	1000	329
	shrink	0	0
	similarity	jaccard	jaccard
	normalize	False	True
UserKNN CF asymmetric	topK	1000	374
	shrink	1000	0
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	2.0000	0.1258
	feature weighting	none	TF-IDF
UserKNN CF tversky	topK	997	414
	shrink	9	71
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.2340	1.1580
	tversky beta	0.1063	1.9364
ItemKNN CF cosine	topK	998	283
	shrink	978	765
	similarity	cosine	cosine
	normalize	True	True
	feature weighting	TF-IDF	BM25
ItemKNN CF dice	topK	1000	78
	shrink	29	2
	similarity	dice	dice
	normalize	True	True
ItemKNN CF jaccard	topK	335	42
	shrink	39	0
	similarity	jaccard	jaccard
	normalize	True	False
ItemKNN CF asymmetric	topK	1000	277
	shrink	544	644
	similarity	asymmetric	asymmetric
	normalize	True	True
	asymmetric alpha	0.0000	0.6317
	feature weighting	TF-IDF	BM25
ItemKNN CF tversky	topK	409	66
	shrink	51	0
	similarity	tversky	tversky
	normalize	True	True
	tversky alpha	0.0216	0.5465
	tversky beta	1.9479	2.0000

Table 112. Hyperparameter values for our non-neural machine learning and graph based baselines on all datasets.

Algorithm	Hyperparameter	Amazon Music	Movielens 1M
$P^3\alpha$	topK	914	406
	alpha	0.5072	1.3317
	normalize similarity	True	True
$RP^3\beta$	topK	833	265
	alpha	0.6294	1.2847
	beta	0.0343	0.5993
	normalize similarity	True	True
$EASE^R$	l2 norm	-	3.25E+03
SLIM BPR	topK	1000	1000
	epochs	140	595
	symmetric	True	True
	sgd mode	adam	adagrad
	lambda i	9.31E-04	1.00E-02
	lambda j	1.00E-02	9.42E-03
	learning rate	1.00E-01	9.93E-03
SLIMElasticNet	topK	1000	502
	l1 ratio	1.30E-04	1.86E-05
	alpha	0.2789	0.0689
MF BPR	sgd mode	adam	adam
	epochs	845	800
	num factors	88	171
	batch size	128	1024
	positive reg	9.10E-04	1.00E-05
	negative reg	4.69E-03	1.00E-05
	learning rate	2.16E-03	2.16E-03
MF FunkSVD	sgd mode	adam	adagrad
	epochs	225	320
	use bias	True	False
	batch size	2	128
	num factors	132	47
	item reg	1.00E-02	2.14E-05
	user reg	1.00E-02	1.28E-03
	learning rate	1.11E-03	3.39E-02
	negative quota	0.3648	0.0941
PureSVD	num factors	58	49
NMF	num factors	64	77
	solver	coord. descent	coord. descent
	init type	nndsvda	random
	beta loss	frobenius	frobenius
iALS	num factors	13	60
	confidence scaling	log	log
	alpha	50.0000	0.5425
	epsilon	0.5407	0.0010
	reg	1.00E-05	1.00E-05
	epochs	90	10

Table 113. Hyperparameter values for the deep learning algorithm on all datasets.

Algorithm	Hyperparameter	Amazon Music	Movielens 1M
DELF MLP	epochs	30	25
	learning rate	1.00E-03	1.00E-03
	batch size	256	256
	num negatives	4	4
	layers	[256, 128, 64]	[256, 128, 64]
	regularization layers	[0, 0, 0]	[0, 0, 0]
	learner	adam	adam
DELF EF	epochs	55	45
	learning rate	1.00E-03	1.00E-03
	batch size	256	256
	num negatives	4	4
	layers	[256, 128, 64]	[256, 128, 64]
	regularization layers	[0, 0, 0]	[0, 0, 0]
	learner	adam	adam

Table 114. Comparison of the computation time for the different algorithms.

	Amazon Music		
	Train time	Recommendation Time	[usr/s]
Random	0.00 [sec]	2.84 [sec]	646
TopPop	0.00 [sec]	3.44 [sec]	533
UserKNN CF cosine	0.10 ± 0.04 [sec]	4.99 ± 0.04 [sec]	366
UserKNN CF dice	0.10 ± 0.00 [sec]	4.98 ± 0.06 [sec]	366
UserKNN CF jaccard	0.10 ± 0.01 [sec]	5.00 ± 0.01 [sec]	367
UserKNN CF asymmetric	0.10 ± 0.01 [sec]	4.97 ± 0.08 [sec]	365
UserKNN CF tversky	0.10 ± 0.00 [sec]	5.01 ± 0.03 [sec]	365
ItemKNN CF cosine	12.41 ± 1.25 [sec]	5.14 ± 0.05 [sec]	354
ItemKNN CF dice	12.74 ± 0.14 [sec]	5.11 ± 0.03 [sec]	357
ItemKNN CF jaccard	12.72 ± 0.12 [sec]	5.01 [sec]	366
ItemKNN CF asymmetric	12.74 ± 0.18 [sec]	5.14 ± 0.02 [sec]	356
ItemKNN CF tversky	13.10 ± 0.17 [sec]	5.13 ± 0.02 [sec]	360
$P^3\alpha$	39.70 ± 1.80 [sec]	5.08 ± 0.01 [sec]	361
$RP^3\beta$	41.92 ± 1.71 [sec]	5.07 ± 0.00 [sec]	362
$EASE^R$	-	-	-
SLIM BPR	1145.90 [sec] / 19.10 ± 9.02 [min]	5.13 ± 0.09 [sec]	357
SLIMElasticNet	1153.77 [sec] / 19.23 ± 6.67 [min]	5.19 ± 0.05 [sec]	354
MF BPR	112.91 [sec] / 1.88 ± 2.68 [min]	3.60 ± 0.02 [sec]	509
MF FunkSVD	285.07 [sec] / 4.75 ± 4.56 [min]	3.88 ± 0.14 [sec]	462
PureSVD	0.74 ± 0.65 [sec]	3.74 ± 0.12 [sec]	498
NMF	568.27 [sec] / 9.47 ± 7.02 [min]	4.14 ± 0.39 [sec]	489
iALS	888.30 [sec] / 14.80 ± 12.32 [min]	3.63 ± 0.02 [sec]	507
DELF MLP	6778.45 [sec] / 1.88 [hour]	405.44 [sec] / 6.76 [min]	5
DELF EF	9427.74 [sec] / 2.62 [hour]	310.86 [sec] / 5.18 [min]	6

Table 115. Comparison of the computation time for the different algorithms.

	Movielens 1M		
	Train time	Recommendation Time	[usr/s]
Random	0.03 [sec]	8.92 [sec]	677
TopPop	0.05 [sec]	9.73 [sec]	621
UserKNN CF cosine	4.63 ± 0.23 [sec]	16.11 ± 0.45 [sec]	383
UserKNN CF dice	4.44 ± 0.19 [sec]	15.72 ± 0.68 [sec]	389
UserKNN CF jaccard	4.45 ± 0.20 [sec]	15.18 ± 0.35 [sec]	393
UserKNN CF asymmetric	4.50 ± 0.19 [sec]	15.84 ± 0.66 [sec]	387
UserKNN CF tversky	4.56 ± 0.22 [sec]	15.86 ± 0.87 [sec]	386
ItemKNN CF cosine	2.13 ± 0.12 [sec]	16.08 ± 0.26 [sec]	375
ItemKNN CF dice	2.09 ± 0.12 [sec]	15.20 ± 0.88 [sec]	414
ItemKNN CF jaccard	2.10 ± 0.13 [sec]	15.73 ± 1.94 [sec]	417
ItemKNN CF asymmetric	2.19 ± 0.15 [sec]	16.66 ± 0.98 [sec]	375
ItemKNN CF tversky	2.13 ± 0.10 [sec]	15.14 ± 0.65 [sec]	420
$P^3\alpha$	4.64 ± 1.45 [sec]	14.66 ± 0.36 [sec]	415
$RP^3\beta$	5.03 ± 1.47 [sec]	14.87 ± 0.49 [sec]	407
$EASE^R$	4.99 ± 0.01 [sec]	13.87 ± 0.11 [sec]	431
SLIM BPR	781.38 [sec] / 13.02 ± 10.84 [min]	15.74 ± 1.06 [sec]	354
SLIMElasticNet	207.72 [sec] / 3.46 ± 2.28 [min]	15.33 ± 0.52 [sec]	401
MF BPR	537.89 [sec] / 8.96 ± 6.05 [min]	10.06 ± 0.24 [sec]	598
MF FunkSVD	2005.64 [sec] / 33.43 ± 36.79 [min]	10.10 ± 0.08 [sec]	600
PureSVD	0.91 ± 0.66 [sec]	10.15 ± 0.10 [sec]	597
NMF	277.51 [sec] / 4.63 ± 14.49 [min]	10.33 ± 0.09 [sec]	587
iALS	315.26 [sec] / 5.25 ± 4.21 [min]	10.13 ± 0.04 [sec]	594
DELF MLP	5479.96 [sec] / 1.52 [hour]	337.65 [sec] / 5.63 [min]	18
DELF EF	7183.43 [sec] / 2.00 [hour]	326.14 [sec] / 5.44 [min]	19

O HYPERPARAMETER RANGE

Table 116. Hyperparameter values for our KNN and graph based baselines.

Algorithm	Hyperparameter	Range	Type	Distribution
UserKNN, ItemKNN cosine	topK	5 - 1000	Integer	uniform
	shrink	0 - 1000	Integer	uniform
	similarity	cosine	Categorical	
	normalize[a]	True, False	Categorical	
	feature weighting	none, TF-IDF, BM25	Categorical	
UserKNN, ItemKNN dice	topK	5 - 1000	Integer	uniform
	shrink	0 - 1000	Integer	uniform
	similarity	dice	Categorical	
	normalize[a]	True, False	Categorical	
UserKNN, ItemKNN jaccard	topK	5 - 1000	Integer	uniform
	shrink	0 - 1000	Integer	uniform
	similarity	jaccard	Categorical	
	normalize[a]	True, False	Categorical	
UserKNN, ItemKNN asymmetric	topK	5 - 1000	Integer	uniform
	shrink	0 - 1000	Integer	uniform
	similarity	asymmetric	Categorical	
	normalize[a]	True	Categorical	
	asymmetric alpha	0 - 2	Real	uniform
	feature weighting	none, TF-IDF, BM25	Categorical	
UserKNN, ItemKNN tversky	topK	5 - 1000	Integer	uniform
	shrink	0 - 1000	Integer	uniform
	similarity	tversky	Categorical	
	normalize[a]	True	Categorical	
	tversky alpha	0 - 2	Real	uniform
	tversky beta	0 - 2	Real	uniform
P3alpha	topK	5 - 1000	Integer	uniform
	alpha	0 - 2	Real	uniform
	normalize similarity[b]	True, False	Categorical	
RP3beta	topK	5 - 1000	Integer	uniform
	alpha	0 - 2	Real	uniform
	beta	0 - 2	Real	uniform
	normalize similarity[b]	True, False	Categorical	

[a]The *normalize* hyperparameter in KNNs refers to the use of the denominator when computing the similarity.
[b]The *normalize similarity* hyperparameter in P3alpha and RP3beta refers to applying L1 regularisation on the rows of the similarity matrix

Table 117. Hyperparameter values for our machine learning baselines.

Algorithm	Hyperparameter	Range	Type	Distribution
SLIM BPR	topK	5 - 1000	Integer	uniform
	epochs	1 - 1500	Integer	early-stopping
	symmetric	True, False	Categorical	
	sgd mode	sgd, adam, adagrad	Categorical	
	lambda i	10^{-5} - 10^{-2}	Real	log-uniform
	lambda j	10^{-5} - 10^{-2}	Real	log-uniform
	learning rate	10^{-4} - 10^{-1}	Real	log-uniform
SLIMElasticNet	topK	5 - 1000	Integer	uniform
	l1 ratio	10^{-5} - 10^{0}	Real	log-uniform
	alpha	10^{-3} - 10^{0}	Real	uniform
MF BPR	num factors	1 - 200[a]	Integer	uniform
	epochs	1 - 1500	Integer	early-stopping
	sgd mode	sgd, adam, adagrad	Categorical	
	batch size	2^{0} - 2^{10}	Integer	log-uniform
	positive reg	10^{-5} - 10^{-2}	Real	log-uniform
	negative reg	10^{-5} - 10^{-2}	Real	log-uniform
	learning rate	10^{-4} - 10^{-1}	Real	log-uniform
MF FunkSVD	num factors	1 - 200[a]	Integer	uniform
	epochs	1 - 500[b]	Integer	early-stopping
	use bias	True, False	Categorical	
	sgd mode	sgd, adam, adagrad	Categorical	
	batch size	2^{0} - 2^{10}	Integer	log-uniform
	item reg	10^{-5} - 10^{-2}	Real	log-uniform
	user reg	10^{-5} - 10^{-2}	Real	log-uniform
	learning rate	10^{-4} - 10^{-1}	Real	log-uniform
	negative quota[c]	0.00 - 0.50	Real	uniform
PureSVD	num factors	1 - 350	Integer	uniform
NMF	num factors	1 - 350	Integer	uniform
	solver	mult. update, coord. descent	Categorical	
	init type	nndsvda, random	Categorical	
	beta loss	kullback-leibler, frobenius	Categorical	
IALS	num factors	1 - 200[a]	Integer	uniform
	epochs	1 - 500[b]	Integer	early-stopping
	confidence scaling	linear, log	Categorical	
	alpha	10^{-3} - $5 \cdot 10^{+1}$ [d]	Real	log-uniform
	epsilon	10^{-3} - 10^{+1} [d]	Real	log-uniform
	reg	10^{-5} - 10^{-2}	Real	log-uniform
EASE R	l2 norm	10^{0} - 10^{+7}	Real	log-uniform

[a]The number of factors is lower than PureSVD or NFM due to the algorithm being slower.
[b]The number of epochs is lower than SLIM BPR or MF BPR due to the algorithm being slower.
[c]The *negative quota* is the percentage of samples chosen among items unobserved by the user, having a target rating of 0.
[d]The maximum value of this hyperparameter had been suggested in the article proposing the algorithm.

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