

RankFromSets: Scalable set recommendation with optimal recall

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We study a variant of user-item recommendation where each item has a set of attributes, such as tags on an image, user reactions to a post or foods in a meal. We focus on the latter example, with the goal of building a meal recommender for a diet tracking app. Meal recommendation is challenging: (i) each item (meal) is rarely logged by more than a handful of users, (ii) the database of attributes (foods) is large, and (iii) each item is tagged with only a handful of attributes. We propose RankFromSets (RFS), a flexible and scalable class of models for recommending items with attributes. RFS treats item attributes as set-valued side information and learns embeddings to discriminate items a user will consume from items a user is unlikely to consume. We develop theory connecting the RFS objective to optimal recall and show that the learnable class of models for RFS is a superset of several previously proposed models. We then develop a stochastic optimization method for RFS that uses negative sampling to scale to massive problems like meal recommendation. In experiments on a real dataset of 55k users logging 16M meals, the new method outperforms competing approaches while learning embeddings that reveal interpretable structure in user behavior. Code is available on GitHub (<https://github.com/altosaar/rankfromsets>).

KEYWORDS

food recommendation, document recommendation, permutation invariant models, content-based recommender systems

1 | INTRODUCTION

Classical recommender systems datasets contain a matrix where each row is a user and each column is an item. Each entry in the matrix indicates whether or not a user consumed an item. Modern applications often gather rich side information about items in the form of a set of attributes or tags. Item attributes provide valuable side information for recommender systems. With a large number of items or a sparse user-item matrix, attribute information is necessary for good performance.

We are motivated by a specific dataset with these properties: a dataset of 55k users logging 16M meals using the Loselt! diet tracking app. Table 1 shows the kind of data logged by users, where each row is an item (meal), each left-hand column is an attribute (food), and each right-hand column is a user. The food attributes can clearly inform recommendations: User 1 does not log meat, User 4 is omnivorous and indiscriminating, and User 3 mostly eats salads. In the Loselt! data there is a massive number of possible items to recommend: there are 12M unique meals, composed of subsets of 3M foods. Meals containing only a few foods or meals at chain restaurants may be logged by many users. But these represent a small proportion of the meals people actually eat, so a long tail of meals are logged by single users.

Work conducted at Princeton University, prior to affiliation with Columbia.

TABLE 1 An example of the data we focus on, where tagged items are recommended to users based on both item attributes and items users have consumed in the past. This example dataset of meals contains meals with different foods (left) and users log which meals they ate (right). The goal is to leverage the attributes to recommend items to users.

| Items | Item Attributes | | | | | | | | | User Identifier | | | | |
|-----------------|-----------------|------|------|-------|---------|---------|----------|------|--------|-----------------|---|---|---|---|
| | Pizza | Eggs | Taco | Salad | Avocado | Chicken | Sardines | Beer | Coffee | 1 | 2 | 3 | 4 | 5 |
| Breakfast Pizza | ● | ● | | | | | | | ● | | ● | | ● | |
| Dinner Pizza | ● | | | | | | ● | ● | | ● | | | ● | |
| Small Salad | | | | ● | ● | | ● | | | | | ● | | ● |
| Big Salad | | ● | | ● | ● | ● | | | ● | | | ● | ● | |
| Taco | | | ● | | ● | ● | | | ● | | | | | ● |
| Fish Taco | | | ● | | | | ● | | | | ● | | ● | |

Modelling item attributes in these recommender systems with long tails of items is not straightforward. Popular ways to use item attributes like multiple matrix factorization (Wang & Blei, 2011; Gopalan et al. 2014) struggle when the attribute vocabulary or the number of items is large. Conversely, simple models are computationally tractable but risk losing the ability to capture nonlinear patterns of user consumption. For instance, a user may enjoy meals tagged with Foods A and B, B and C, or A and C, but not all three. Finding the right balance between scalability and flexibility is therefore a primary goal.

Even when a model can be scaled, it may not be clear how its training procedure connects to the recommender system evaluation metric. A matrix factorization method might minimize mean squared error when the recommender system is evaluated on recall. While it is plausible that minimizing mean squared error will improve recall, the connection between the two is implicitly assumed in many methods. Ideally, a recommender system should have an objective that matches its evaluation metric.

This paper proposes RankFromSets (RFS), a class of principled, scalable models for recommending items with sets of attributes. RFS casts the recommendation problem as binary classification. Given a user and an item, RFS treats attributes as features and classifies whether or not the item is likely to be consumed by the user. RFS learns embeddings for each user and attribute; each item is represented as the mean of its attribute embeddings. To scale to large datasets, we develop an RFS method that is trained using negative sampling of random items that are unlikely to be consumed.

RFS enjoys two benefits from framing the recommendation problem as classification. First, the RFS classification objective function is directly tied to recommender recall: we show that a classifier with zero worst-case error achieves maximum recall. Second, RFS is provably flexible enough to learn any class of recommendation model based on set-valued side information (including multiple matrix factorization). This generality makes RFS a natural drop-in replacement for many specialized models in the literature.

We study the performance of the negative sampling RFS model on a semisynthetic benchmark dataset and the Loselt! dataset. The semisynthetic paper recommendation dataset consists of 65k users clicking on 636k papers posted to the arXiv; the attributes of each paper are the unique words in its abstract. We then apply the method to the Loselt! dataset to make out-of-sample meal recommendations. In both cases, RFS outperforms the state of the art in terms of recall. In addition to good performance, the RFS model learns interpretable embeddings that capture the structure of the underlying data.

2 | RANKFROMSETS

RankFromSets (RFS) is a class of recommendation models that recommend items with attributes to users. Let $u \in \{1, \dots, N\}$ be a user, $m \in \{1, \dots, M\}$ be an item, and $y_{um} \in \{0, 1\}$ be a binary indicator where 1 indicates user u consumed item m . For each item m , there is an associated set of attributes $x_m \in \{0, 1\}^{|V|}$ from a vocabulary of V attributes. The observed data are a collection of user-item interactions $\{(u, m)\}$ and the sets of attributes associated with items $\{x_m\}$.

We assume that a recommendation model is given a budget of K recommendations to be made for each user. In response, the recommender system produces a list of K distinct recommendations $\mathbf{r}_u = (r_{u1}, \dots, r_{uK})$ for each user. The goal of the recommendation task in this paper is to maximize the expected Recall@K:

$$\text{Recall@K} = \mathbb{E}_u \left[\frac{\sum_{r \in \mathbf{r}_u} y_{ur}}{\sum_m y_{um}} \right], \quad (1)$$

with the expectation over users in the empirical distribution \mathcal{D} .

We combine three techniques to maximize Recall@K with RFS. First, we cast recommendation as a classification task. Second, we learn user- and attribute-level embeddings. Statistical strength is shared between items with similar attributes by representing items as the mean of their attribute embeddings. Third, we scale RFS to large datasets using a stochastic optimization-based negative sampling training procedure.

RFS casts the recommendation problem as a classification task. Given a user-item pair (u, m) and a regression function f , RFS learns to predict the probability that item m will be consumed by user u :

$$p(y_{um} = 1 | u, m) = \sigma(f(u, x_m)),$$

where x_m is the set of attributes of item m and σ is the sigmoid function. Recommendations made by RFS are the maximum likelihood set formed by ranking a set of items for a user according to the model $f(u, x_m)$. We motivate treating recommendation as classification with the following observation.

Proposition 1. Let $u \in \mathcal{U}$ be a user, $m \in \mathcal{M}$ be an item, and $y(u, m) \in \{0, 1\}$ be an indicator of whether user u logged item m . Let \mathcal{E} be the worst-case error for binary classifier $\hat{y}(u, m)$ on any (u, m) pair drawn from the data \mathcal{D} ,

$$\mathcal{E} = \max_{(u, m) \in \mathcal{D}} \mathbb{I}[\hat{y}(u, m) \neq y(u, m)].$$

A binary classifier with zero worst-case error ($\mathcal{E} = 0$) maximizes recommendation recall.

Proof. A model with zero worst-case error is a perfect classifier, assigning greater probability to data with positive labels than to data with negative labels. In other words, it ranks positive examples above negative examples. Recall@K is measured by the fraction of items with positive labels in a ranking returned by the model. In a classifier that achieves zero worst-case error, positively labeled datapoints must be ranked higher than other datapoints, maximizing recall. \square

Proposition 1 is simple but conceptually important. For a dataset for which a perfect (zero worst-case error) classifier exists, a consistent method for learning a classifier will be a consistent method for learning a recommendation system that targets expected recall. Put another way, recall is inherently binary: a model does or does not recall an item; an item is or is not in the top K recommendations in the numerator of Equation (1). So the best one can hope to do if recall is used to assess recommendation performance is to train a binary classifier. In practice, as with any regression method, a perfect classifier is unachievable. Proposition 1 is a guiding principle rather than a finite-sample guarantee of maximal performance. As we show in Section 4, the classification approach of RFS performs well in practice.

For recommending items with attributes, Proposition 1 says that building a classifier such as RFS is optimal if we measure recommendation performance with recall. To parameterize the RFS classifier, a regression function $f(u, x_m)$ is needed. A straightforward parameterization is an inner product:

$$f(u, x_m) = \theta_u^\top \left(\frac{1}{|x_m|} \sum_{j \in x_m} \beta_j + g(x_m) \right) + h(x_m). \quad (2)$$

Each element in the inner product regression function in Equation (2) has an intuitive interpretation. The user embedding $\theta_u \in \mathbb{R}^d$ captures the latent preferences for user u . This captures the individual-level tastes of a user and is analogous to the user preference vector in classical collaborative filtering or the row embedding in matrix factorization. The attribute embedding $\beta_j \in \mathbb{R}^d$ is the latent quality conveyed through item m having attribute j . (The set x_m contains only attributes with $x_{mj} = 1$. Attributes that are not associated with item m are ignored.) The item embedding function $g(x_m) \in \mathbb{R}^d$ represents qualities not conveyed through the set of item attributes. This term in the regression function enables collaborative filtering by capturing unobserved patterns in item consumption such as popularity. We describe how to construct this function below. The scalar item intercept function $h(x_m) \in \mathbb{R}$ makes an item more or less likely due to availability.

To define scalable item embedding and item intercept functions, note that the parameterization of the item embedding function $g(x_m)$ depends on the size of the data. If the number of items is small, g can function as a lookup for unique intercepts for every item. However, if the number of items is so large that unique item intercepts lead to overfitting, a scalable parameterization of item embeddings g can be defined using additional information about every item. For example, if the data consist of foods in meals, we can define a meal intercept as the mean of food intercepts, yielding a scalable item intercept function. The item intercept function $h(x_m)$ that maps item attributes to scalars is constructed in the same way. We study both of these choices in Section 4.

The inner product regression function in Equation (2) has several benefits. It requires computing a sum over only the attributes with which each item is associated. This enables RFS to scale to large attribute vocabularies where traditional matrix factorization methods are intractable. Second, the embed-and-average approach to set modelling is provably flexible as we show later. We now describe deep variants of RFS and detail how RFS can approximate other recommendation models.

The RFS inner product regression function in Equation (2) is a log-bilinear model. But there are several other choices of regression function, and we draw on the deep learning toolkit for classification to build two other example architectures. With finite data and finite computation, one architecture may outperform another or prove insufficient to capture patterns in user consumption. (Later, we describe a more general class of models which can, in theory, achieve the same performance.) First, as an alternative to the log-bilinear model in Equation (2), we can use a deep neural network as a regression function:

$$f(u, x_m) = \phi \left(\theta_u, \frac{1}{|x_m|} \sum_{j \in x_m} \beta_j, g(x_m) \right) + h(x_m), \quad (3)$$

where the deep network ϕ has weights and biases and takes as inputs the user embedding, sum of attribute embeddings and item intercept. Such a neural network can represent functions that may or may not include the inner product in Equation (2); *ex ante*, it is unclear whether a finite-depth, finite-width neural network can represent the inner product.

Another regression function for RFS is a combination of Equations (2) and (3), using an idea borrowed from deep residual networks for image classification (He et al. 2016). In this architecture, a neural network ϕ with the same inputs as in Equation (3) learns the residual of the inner product model:

$$f(u, x_m) = \theta_u^\top \left(\frac{1}{|x_m|} \sum_{j \in x_m} \beta_j + g(x_m) \right) + \phi + h(x_m). \quad (4)$$

The choice of regression function in RFS depends on the data. On finite data with finite computation, one parameterization of RFS will outperform another. To demonstrate this, we simulated synthetic data from the same generative process RFS employs with a ground-truth regression function (a square kernel) and found that the residual and deep parameterizations outperformed the inner product architecture. These results are included in Appendix S1.4 and motivate exploring other architectures than the three examples here.

Stepping back from the setting of finite data and computation, a bigger picture emerges which reveals that the choice of regression function in RFS does not matter. We show that any RFS architecture is sufficiently flexible to approximate recommendation models that operate on set-valued inputs. We define permutation invariant models before deriving this result.

The regression function f in RFS operates on set-valued inputs: the unordered collection of item attributes x_m . A set is, by definition, permutation invariant: it remains the same if we permute its elements. Functions that operate on set-valued inputs must also be permutation invariant. RFS is permutation invariant, as the set of attributes associated with an item enter into Equations (2)–(4) via summation. Other examples of permutation invariant recommendation models are multiple matrix factorization, models based on word embeddings, and permutation-marginalized recurrent neural networks. These models are shown to be permutation invariant in Section 3 and are evaluated in Section 4. We now show that RFS can approximate other permutation invariant recommendation models such as matrix factorization.

Proposition 2. Assume the vocabulary of attributes (set elements) is countable, $|V| < |\mathbb{N}_0|$. Then RFS can approximate any permutation invariant recommendation model.

The proof follows directly from Theorem 2 in Zaheer et al. (2017), and we will not restate it here. (The only change to the proof is the mapping from set elements to one-hot vectors, $c: V \rightarrow \{0, 1\}^{|V|}$, to yield a unique representation of every object in the powerset.) Proposition 2 means that any of the parameterizations in Equations (2)–(4) is flexible enough to approximate other principled recommendation models that leverage item attributes, such as multiple matrix factorization (Gopalan et al. 2014; Wang & Blei, 2011).

The parameters for RFS are learned by stochastic optimization. Denote the full set of RFS model parameters by γ , and let \mathcal{D}_u be the empirical data distribution for a user. Let λ_u be a reweighting parameter. The per-user maximum likelihood objective for RFS is

$$\mathcal{L}(\gamma, \lambda_u) = \mathbb{E}_u \left[\mathbb{E}_{m \sim \mathcal{D}_u} \mathbb{1}_{y_{um} = 1} [\log p(y_{um} = 1 | x_m; \gamma)] + \lambda_u \mathbb{E}_{k \sim \mathcal{D}_u} \mathbb{1}_{y_{uk} = 0} [\log p(y_{uk} = 0 | x_k; \gamma)] \right] \quad (5)$$

In traditional regression, altering the ratio of positive to negative examples by reweighting leads to inconsistent parameter estimation. The inconsistency stems from the randomness in the labels given the features. However, Recall@K assumes that each user, item attribute set pair

(u, x_m) , uniquely determines whether the item was consumed or not (the label y_{um}). Here, all reweightings produce the same result. This means that for any negative example weight λ_u the learned model will be the same. In practice, we set λ_u to balance the positive and negative examples for each user. We use stochastic optimization to maximize Equation (5) and describe two negative sampling schemes that are dependent on the choice of evaluation metric.

Negative samples can be drawn uniformly over the entire corpus of items, which we define to be corpus sampling. If the item set is large, this can be an expensive procedure. This negative sampling scheme leads to objective functions used in other recommender systems (He et al. 2017; Song et al. 2018).

On large datasets it is infeasible to calculate Recall@K for evaluation, as this requires ranking every item for every user (e.g., in Section 4, we study a dataset with over 10M items). We define a scalable evaluation metric based on recall and describe how it leads to a natural choice of negative sampling distribution.

Sampled recall is defined as follows. Consider held-out datapoints with positive labels, $(x_m, y_{um} = 1)$. For every held-out datapoint, $K - 1$ datapoints with negative labels $(x_k, y_{uk} = 0)$ are sampled from the rest of the held-out data, which together yield a set of K datapoints. A recommendation model is used to rank the K datapoints r_{u1}, \dots, r_{uK} . SampledRecall@k is the fraction of the K held-out datapoints that the model ranks in the top k :

$$\text{SampledRecall@k} = \frac{1}{K} \mathbb{E}_{um} \left[\sum_{r \in \{r_{u1}, \dots, r_{uK}\}} y_{ur} \right]. \quad (6)$$

The expectation is over users and items in the held-out set of datapoints. This evaluation metric is scalable: instead of using a model to rank every item, SampledRecall@k requires ranking only K items. Sampled recall is 1 if $k = K$, as the held-out datapoint with $y_{um} = 1$ is in each list of K datapoints to be ranked. This metric is used in recommender systems when the number of items is large (Ebesu et al. 2018; Yang et al. 2018).

When sampled recall is used as an evaluation metric, batch sampling is a natural way to draw negative samples. Sampled recall is calculated on items drawn from other users' data. We define batch sampling as generating negative samples by permuting mini-batch items. Besides corresponding to the sampled recall metric, this technique is memory efficient, as it requires that only the current mini-batch be in memory.

In addition to scalability, both negative sampling procedures above have the advantage of implicitly balancing the classifier. As shown in Veitch et al. (2019), using the stochastic gradient descent with negative sampling is equivalent to a Monte Carlo approximation of the reweighted (balanced) classification loss.

3 | PERMUTATION INVARIANT RECOMMENDATION MODELS

Proposition 2 shows that RFS can approximate permutation invariant recommendation models. We describe several common recommendation models and show that they are permutation invariant, before comparing their performance to RFS in Section 4.

Gopalan et al. (2014) develop a probabilistic matrix factorization model of user consumption data. Collaborative topic Poisson factorization (CTPF) models user preferences using a generative process,

1. Document model:
 - (a) Draw topics $\beta_{vk} \sim \text{Gamma}(a, b)$
 - (b) Draw document topic intensities $\theta_{dk} \sim \text{Gamma}(c, d)$
 - (c) Draw word counts $w_{dv} \sim \text{Poisson}(\theta_d^T \beta_v)$.
2. Recommendation model:
 - (a) Draw user preferences $\eta_{uk} \sim \text{Gamma}(e, f)$
 - (b) Draw document topic offsets $\epsilon_{dk} \sim \text{Gamma}(g, h)$
 - (c) Draw $r_{ud} \sim \text{Poisson}(\eta_u^T (\theta_d + \epsilon_d))$.

To show that CTPF is permutation invariant, consider the Poisson likelihood function over words w_{dv} . Conditional on the latent item representation θ_d and the latent word representation β_v , every word in the document w_{dv} is independent; the joint probability of words in a document factorizes:

$$p(w_d | \theta_d, \beta_v) = \prod_{w_{dv} \in w_d} p(w_{dv} | \theta_d, \beta_v). \quad (7)$$

CTPF makes predictions using expectations under the posterior. The posterior is proportional to the log joint of the model, and the attributes of items (words in documents) enter into the model only via the above product. The product of the probability of words in a document is invariant to a reordering of the words in the document, and therefore, CTPF is permutation invariant.

Word embedding models (Mikolov et al. 2013) can be used as recommendation models if the embeddings are learned using a modified context window. For an item with attributes x_m , let the context window for attribute $j \in x_m$ be the set of other attributes of the same item $j' \in x_m : j' \neq j$. To recommend items using this model of attributes β_j for $j \in V$, item embeddings are computed as the average of their attribute embeddings. Users are represented as the average of the embeddings of the items they consume, and recommendation is performed using the cosine similarity of user and item embeddings. This is a permutation invariant model, as the output of the model depends on the sum of attribute embeddings (summation is invariant to permutation).

StarSpace is also an embedding model and represents users as a sum over a user's consumed items' attribute embeddings (there is no explicit user embedding). In contrast to the word embedding model, StarSpace is trained on a classification objective with negative samples drawn from the set of items (Wu et al. 2018). As model predictions depend on sums of attributes, StarSpace is a permutation invariant recommendation model.

We next consider LightFM (Kula, 2015), a permutation invariant recommendation model. We show that if the Bayesian Personalized Ranking (BPR) objective (Rendle et al. 2009) is used, LightFM is an instance of RFS.¹ Although the BPR objective is designed for ranking, models trained with it can be used to construct classifiers. The BPR objective is

$$\log \sigma(f(u, x_m; \gamma) - f(u, x_k; \gamma)),$$

where m corresponds to a positive label $y_{um} = 1$, k corresponds to a negative label $y_{uk} = 0$, and f is parameterized as in RFS (Kula, 2015). A ranking function f optimizes the BPR objective if $f \rightarrow \infty$ for the positive example and f is constant for the negative example, or if f is constant for the positive example and $f \rightarrow -\infty$ for the negative example. In either case, a constant can be added to yield a perfect classifier from the ranking function f (positive examples are ranked higher than negative examples in the optimal ranking, so there exists such a constant). That we can construct a classifier from the BPR objective means that Proposition 1 applies: permutation invariant models such as LightFM, trained with the BPR objective, are instances of the RFS class of recommendation models.

The regression function f in RFS can also be parameterized using a recurrent network, as in Bansal et al. (2016). Such a recommendation model can be made permutation invariant if averaged over permutations of attributes fed to the network. Attributes are treated as a sequence, and the marginalization is over these permutations:

$$p(y_{um} = 1 | x_m) = \frac{1}{|\pi(x_m)|} \sum_{\pi \in \pi(x_m)} \sigma(\phi(\theta_u, \{\beta_{\pi(1)}, \dots, \beta_{\pi(J)}\})). \quad (8)$$

Here, β_j are attribute embeddings, $\pi(x_m)$ denotes the set of all permutations of the attributes x_m , and ϕ is the output of a recurrent neural network architecture (Bansal et al. 2016) projected to a scalar.

4 | EMPIRICAL STUDY

We study RFS on two datasets and tasks. The first data consist of researcher reading behavior from the arXiv; the semisynthetic task is to recommend documents to scientists. The second is crowdsourced food consumption data from a diet tracking app, and the task is meal recommendation. On both benchmarks, models in the RFS class outperform several baseline methods. The permutation invariant models we compare to are described in Section 3, and the hyperparameters used are described in Appendix S1.1. To show the relative ease of implementation of RFS, we give example code in Appendix S1.5.²

4.1 | Recommending Research Papers

We benchmark RFS on data of scientists reading research papers on the arXiv, where the goal is to recommend papers to scientists. This is a semisynthetic task: it uses real-world data, but the item side information (article abstracts) is not set valued. Nevertheless, document recommendation is a standard benchmark to study whether RFS performs well in settings outside its target purview of meal recommendation. The arXiv data

¹The LightFM paper (Kula, 2015) uses a logistic objective to which Proposition 1 applies. LightFM with the BPR objective is unpublished but implemented in code released by the author. For completeness, we studied LightFM with both objectives to ensure its performance is equivalent to RFS when the BPR objective is used.

²Full source code is available at <https://github.com/altosaar/rankfromsets> for reproducibility.

represent 1 year of usage (2012) and consist of 65k users, 636k preprints, and 7.6M clicks. For evaluation, we match Gopalan et al. (2014), using the same test and validation splits and the same set of held-out 10k users. As in Gopalan et al. (2014), we compute precision in addition to recall. The held-out validation and test splits each consist of 20% of the clicks and 1% of the documents. In-matrix documents refer to documents that have clicks in the training data, while out-matrix or cold-start documents have no previous clicks.

Figure 2 shows that models in the RFS class outperform others. RFS with the inner product parameterization or LightFM with the BPR objective has identical performance (as we showed, the BPR objective yields a classifier equivalent to RFS). These RFS models outperform CTPF in terms of in-matrix recall by over 90%. RFS models also improve over CTPF in terms of out-matrix recall, out-matrix precision, and in-matrix precision. The word embedding model performs comparably to CTPF in terms of recall and performs worse in terms of precision. Recurrent neural network recommendation models were implemented following Bansal et al. (2016) and given access to full sequence information, unlike RFS. (The permutation-marginalized version of these models in Equation (8) is evaluated on meal recommendation where the order of foods in a meal does not carry information.) The training details for the recurrent neural networks are in Appendix S1.1, but their performance was an order of magnitude worse than the other methods and these results are omitted. The RFS regression function used is in Equation (2); the other parameterizations did not fit in GPU memory.

Qualitatively, RFS reveals patterns in usage of the arXiv. Figure 1 is a dimensionality-reduced plot of the user embeddings that reveals connections between fields of study. Scientists who focus on high energy physics, `hep`, neighbour specialists in differential geometry, `math.DG`;

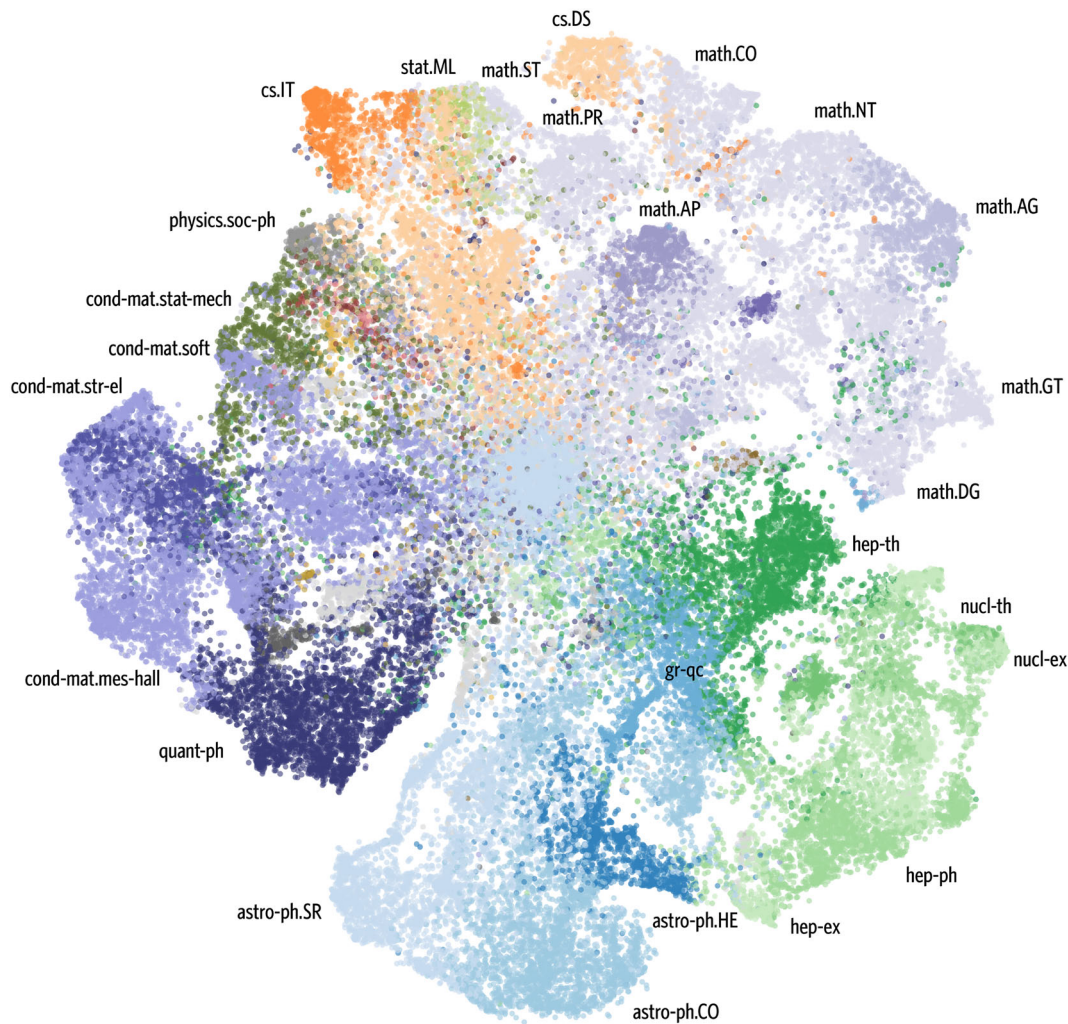


FIGURE 1 RankFromSets trained on arXiv reading behavior clusters researchers by their most frequently read arXiv category (best viewed on a screen). RFS is trained to recommend items using their attributes (words in the abstract). t-SNE (Maaten & Hinton, 2008) is used to visualize the user embeddings θ_u in the inner product regression function in Equation (2). Each marker represents a user embedding; its colour represents a user's most-read arXiv category. Unique colours are determined using the most-read categories across the arXiv, and colours are assigned according to the arXiv ontology. RFS captures usage patterns, as fields of study are related by patterns of reading behavior across neighbouring fields (e.g., `stat.ML` and `cs.IT`). An interactive version of this figure can be accessed at <https://jaan.io/files/rankfromsets-arxiv.html>

these areas share techniques. Machine learning researchers (`stat.ML` readers) neighbour statisticians (`math.ST` readers), highlighting the close connection between these fields. Plots for document embeddings show similar patterns. This illustrates how RFS captures rich patterns of interactions between users and items while benefitting from information in the item attributes.

This experiment in recommending research papers also highlights a trade-off in computational budget and desired performance in recommender systems. As described in Appendix S1.2, the recurrent neural network recommendation models in Bansal et al. (2016) did not perform well with the computational budget allocated for all methods (one day of computation on a Tesla P100 GPU). In further experiments, the performance improved marginally with a larger computational budget of several days. Further research in this domain might compare to transformer models (Vaswani et al. 2017, Devlin et al. 2019). Transformers preserve sequence information, unlike RFS, although they require large computational budgets to make accurate predictions. This means transformer-based methods may present a different trade-off in recommendation performance than the recurrent neural networks we evaluated in this task (Figure 2).

4.2 | Recommending Meals

We evaluate RFS on data collected from the LoseIt! diet tracking app. This app enables users to track their food intake to eat healthy. We use a year's worth of data from 55k active users. This corresponds to 16M meals, where each meal is composed of a subset of 3M foods. To preprocess, we filter the vocabulary by keeping words that occur at least 20 times in the food names, resulting in 9963 words. A meal is represented as the union of the sets of words occurring in the food names. For evaluation, 1% of the items (meals) are held out for evaluating validation and test performance respectively. We evaluate models using `SampledRecall@K` with $K = 10$.

Figure 3 shows the sampled recall: models in the RFS class outperform others, such as permutation-marginalized recurrent neural networks and word embedding models. The residual RFS model outperforms the RFS inner product parameterization (and the equivalent LightFM model trained on the BPR objective). The code released with Gopalan et al. (2014) or Wang and Blei (2011) did not scale to this size of data, despite sufficient computing resources. This experiment further verifies Proposition 1: RFS models can maximize recall.

Qualitatively, RFS learns an interpretable representation of items, as shown by nearest neighbours of meals in Table 2. In this table, we display breakfast, lunch, and dinner meals, alongside their nearest neighbours. We find that the nearest neighbours are also breakfast, lunch, and dinner meals, respectively, showing that the attribute embeddings learned by the model can be used to explore qualitative patterns in the learned latent space.

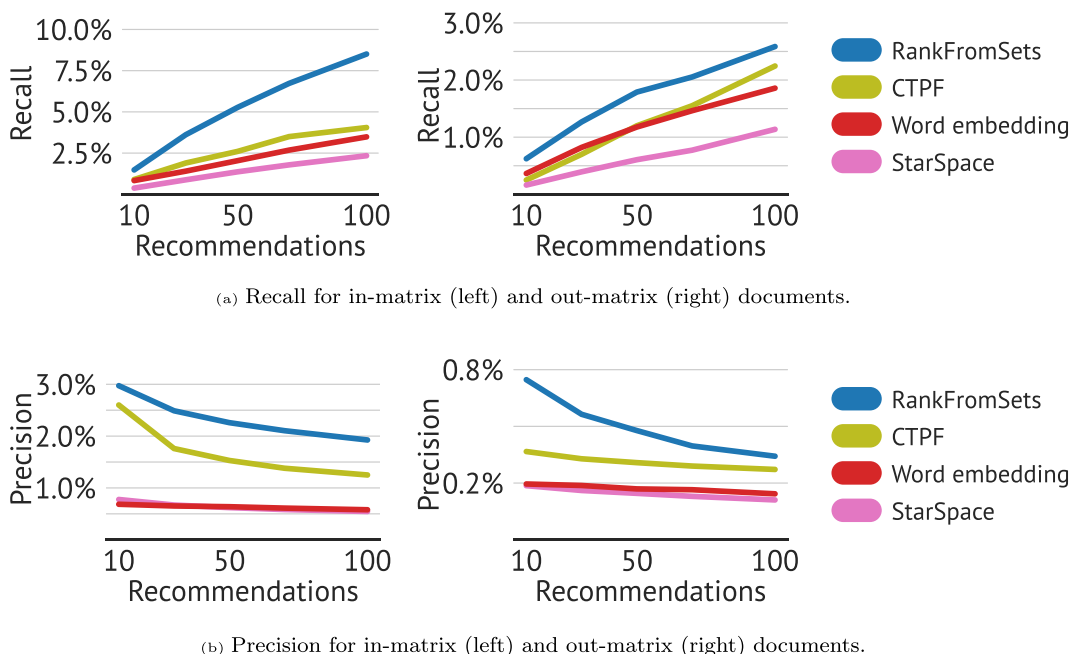


FIGURE 2 RankFromSets outperforms collaborative topic Poisson factorization (CTPF) (Gopalan et al. 2014) and other models on recommending arXiv papers to scientists. The items are documents and the attributes are the unique words in the abstracts. Recommendation performance is evaluated using both precision and recall to match the evaluation in Gopalan et al. (2014). The metrics are reported on training (in-matrix) documents and cold-start (out-matrix) documents with no clicks in the training set. All GRU and LSTM-based models in Bansal et al. (2016) performed an order of magnitude worse, and these results are omitted (training details are in Appendix S1.1)

FIGURE 3 RankFromSets models outperform competitors in meal recommendation in terms of sampled recall computed using Equation (6). Comparison models are described in Section 3 (see Appendix S1.1 for hyperparameters). The RFS regression functions f are defined in Equation (2)–(4) for the inner product, neural networks, and residual models, respectively

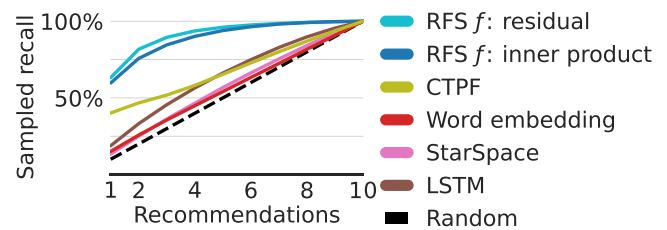


TABLE 2 RankFromSets trained on food consumption data provides diverse meal recommendations.

| Query item | Nearest item by cosine similarity |
|--|---|
| Two scoops of raisin bran cereal, organic Moroccan green tea, almond milk, light honey, tap water, large banana and large strawberries | Vita Bee bread, salted butter, fresh medium tomatoes, large fried whole egg and small banana |
| Iceberg lettuce, cantaloupe cubes, diced honeydew melon, cherry tomatoes, olives, dry-cooked unsalted hulled sunflower seed kernels, chopped hard-boiled egg, cucumbers, dried cranberries and fat-free ranch dressing | Green leaf lettuce, chopped sweet red bell peppers, crumbled feta cheese, large hard-boiled egg, chopped cucumber, oil-roasted salted sunflower seeds, sliced radishes, sliced strawberries, pitted Calamata olives and fat-free balsamic vinegar |
| Boston roast pork, mackerel, artichoke hearts, spinach, pimiento-stuffed Manzanilla olives, carrots, mushrooms and pecorn ranch dressing | Broiled top round steak, tomatoes, cucumber, baby yellow squash, zucchini, black olives and extra virgin olive oil |
| Meatloaf with tomato sauce, chopped sweet red bell peppers, extra virgin olive oil, cooked asparagus spears, sweet potatoes, orange and cantaloupe cubes | Chicken breast, breadcrumbs, fresh tomatoes, shredded green leaf lettuce, extra virgin olive oil, spinach, chopped yellow onion, sweet large yellow bell peppers, whole mushrooms, chili peppers and vinaigrette |
| Ciabatta bun, cooked skinless chicken breast, fresh baby spinach, shredded iceberg lettuce, shredded mozzarella cheese, ketchup and frozen yogurt bar | Small whole wheat submarine roll, broiled round roast beef, roasted light turkey meat without skin, fresh medium tomatoes, honey smoked ham, shredded iceberg lettuce and sliced mozzarella cheese |

Note: RankFromSets (RFS) with Equation (4) is fit to data from a diet tracking app; items are meals and attributes are the ingredients in the meal. Meals are represented the average of their attribute embeddings, and cosine similarity between meal representations is used to find the nearest neighbours of meals (user-level information cannot be shown as these are personal diet data). RFS reveals eating patterns: for example, the second-last query meal is a mix of meat, vegetables, and fruit, and the nearest neighbour meal is a different meat with a side of salad; the last query meal is a sandwich, and its nearest neighbour is also a sandwich with different ingredients.

5 | RELATED WORK

We survey food recommender systems and recommendation models, focusing on models that leverage content information and scale to large numbers of users, items, and attributes.

Existing food recommendation systems focus on healthy recommendation (Trattner & Elswailer, 2019a; Freyne et al. 2011; Khan et al. 2019; Yang et al. 2017), while RFS focuses on the scalability challenge of meal recommendation. After training a recommendation model, it is possible to filter the recommendations by nutritional information to nudge users towards healthier eating habits (Elswailer et al. 2017); such approaches can be used to include nutritional information into RFS recommendations. When data are used in food recommender systems, it is usually recipe data (Trattner & Elswailer, 2018); RFS is designed to recommend meals using crowdsourced food consumption data, which may accurately reflect user behavior (Trattner & Elswailer, 2019b).

We highlight several themes in research on recommendation models. We describe recommendation models that incorporate side information, models that recommend through classification and models that optimize proxies of ranking metrics. This related work is summarized in Table 3. We focus on deep learning-based and matrix factorization methods to include side information in recommendation models. Item side information can be modelled with deep representations or can be included in content-based matrix factorization models as an additional matrix. Some deep learning approaches scale to large datasets but may not have objective functions tied to evaluation metrics or may require data beyond user-item interactions (Okura et al. 2017). Content-based matrix factorization methods require learning parameters for every item and do not scale to data with large numbers of items (Wang & Blei, 2011; Gopalan et al. 2014), whereas RFS scales and is tied to evaluation.

5.1 | Deep Representations of Side Information

Deep learning-based recommendation models incorporate side information in multiple ways (Zhang et al. 2019). For example, items that have words as attributes can be represented using neural networks (Bansal et al. 2016; Chen & de Rijke, 2018) or embeddings (Wu et al. 2018). RFS uses both embeddings and deep learning techniques such as residual networks (He et al. 2016) to include side information. Lian et al. (2018) use an attention mechanism to weight recommendations according to available item and user side information, and Dong et al. (2017) use denoising autoencoders to model side information in a deep recommendation model, but these methods require fitting parameters for every item and hence cannot scale. An example of a more efficient approach is the method in Chen et al. (2017), where embeddings are jointly learned for users, items, and item text for recommendation, but this method focuses on unsupervised pretraining of text representations. RFS is complementary to such approaches, as the user, attribute, and item embeddings can be initialized using pre-training. Deep structured semantic models are designed for document retrieval given query words (Huang et al. 2013; Palangi et al. 2016); it is unclear how to use this setup for recommending items with set-valued side information to users. There are several examples of ‘tag-aware’ or ‘tag-based’ deep recommendation models (Liang et al. 2018; Zuo et al. 2016), such as Xu et al. (2017), which focuses on data where users and items have different attributes and uses autoencoders to learn user, item, and attribute representations. Xu et al. (2017) use a cosine similarity-based objective function, which is not tied to a metric used to evaluate recommendation performance, whereas RFS is tied to recall as shown in Proposition 1.

5.2 | Recommendation via Classification

The framing of recommendation as classification has been around for a long time (Basu et al. 1998), and several works build deep learning-based classifiers for recommendation (Covington et al. 2016; Cheng et al. 2016; Guo et al. 2017; He et al. 2017). Covington et al. (2016) focus on scalable inclusion of user and item attributes for video recommendation, Cheng et al. (2016) jointly train generalized linear models and deep neural networks for recommendation, while Guo et al. (2017) use factorization machines to learn high- and low-order interactions of features. Our work is complementary to these approaches: RFS focuses on scalable inclusion of set-valued side information and provides theoretical undergirding to these recommendation models. We connect such models that rely on classification to optimal recall in Proposition 1. And if a specific architecture developed in these works is a permutation invariant recommendation model, we proved that RFS is a universal function approximator (Proposition 2). So if performance is measured by recall, an RFS model can converge to an optimal recommender.

TABLE 3 RankFromSets recommends items using attributes and is trained to maximize the evaluation metric of recall

| Model | Attributes | Implicit | Scalable | Invariant | Evaluation |
|--|------------|----------|----------|-----------|------------|
| RankFromSets | ✓ | ✓ | ✓ | ✓ | ✓ |
| CTPF, Gopalan et al. (2014) | ✓ | ✓ | | ✓ | |
| StarSpace, Wu et al. (2018) | ✓ | ✓ | ✓ | ✓ | |
| LightFM, Kula (2015) | ✓ | ✓ | ✓ | ✓ | |
| BPR, Rendle et al. (2009) | | ✓ | | | ✓ |
| Wang and Blei (2011) | ✓ | ✓ | | ✓ | |
| Lian et al. (2018) | | | ✓ | | |
| Dong et al. (2017) | ✓ | | | ✓ | |
| T. Chen, et al. (2017) | ✓ | | ✓ | | |
| T. Bansal et al. (2016) | ✓ | ✓ | | | |
| Xu et al. (2017) | ✓ | | ✓ | ✓ | |
| Shi, Karatzoglou, Baltrunas, Larson, Oliver, and Hanjalic (2012) | | ✓ | | | ✓ |
| Y. Chen and de Rijke (2018) | ✓ | ✓ | | ✓ | |
| Liu et al. (2014) | ✓ | | | ✓ | ✓ |
| Cao et al. (2017) | ✓ | | | | ✓ |
| Okura et al. (2017) | ✓ | | ✓ | | ✓ |

Note: Most methods we highlight leverage item attributes (Attributes); some require data in addition to the implicit feedback data of user-item interactions (Implicit). Few methods are scalable, as most models that use item side information require learning parameters for every item. Some models are invariant to permutation of the attributes (Invariant), and some enjoy a loss function that is connected to a recommender performance metric (Evaluation).

5.3 | Matrix Factorization with Side Information

While matrix factorization methods perform well in recommending items that have consumption data in the training set (Hu et al. 2008; Liang et al. 2016), they cannot recommend items that have not been consumed in the training data. Including side information in matrix factorization enables recommendation of these items with no consumption data. Shi et al. (2014) survey several matrix factorization methods that leverage side information. Gopalan et al. (2014) develop a Bayesian matrix factorization model for recommending items based on side information in the form of words in documents, and we compare RFS to this method in Section 4. Wang and Blei (2011) develop a regression model that uses a topic model to incorporate side information into recommendations. There are also several 'tag-based' or 'tag-aware' content-based matrix factorization models (Zhen et al. 2009; Loepp et al. 2019; Bogers, 2018). Such content-based matrix factorization methods maximize the conditional log-likelihood of the data (or a bound on the log-likelihood); optimizing these objective functions may not optimize an evaluation metric. These methods are not scalable to large numbers of items as they require learning unique parameters for every item. Specifically, such content-based matrix factorization methods require learning a matrix that has a row for every item. For items with attributes, it is often infeasible to store this matrix in memory or exploit efficient coordinate ascent optimization schemes that require processing this entire matrix. RFS, however, is designed to scale to tens of millions of items, as we demonstrate empirically in Section 4.

5.4 | Learning to Rank

The learning to rank literature includes several recommendation models trained on objectives that approximate ranking-based evaluation metrics (Yu et al. 2018; Liang et al. 2018; Rendle et al. 2009; Song et al. 2018), and some of these models include side information (Shi, Karatzoglou, Baltrunas, Larson, Hanjalic, & Oliver, 2012; Shi, Karatzoglou, Baltrunas, Larson, Oliver, & Hanjalic, 2012; Yuan et al. 2016; Ying et al. 2016; Cao et al. 2017; Okura et al. 2017). Such approaches can require data in addition to the user-item matrix, such as per-item parameters, or might use models whose output depends on the ordering of item attributes (making them infeasible for set-valued side information). In Section 4, we show that the ranking-based BPR objective function (Rendle et al. 2009; Kula, 2015) is in the RFS class, so Proposition 1 can help frame this related work. Li et al. (2016) use an objective that is in the same class as BPR and other work bounds the BPR objective (Zhang et al. 2018); these are also examples of RFS models if a permutation invariant architecture is specified and we study one such choice (Kula, 2015) in Section 4.

6 | DISCUSSION

The task of recommending items with attributes is difficult for several reasons. It is unclear how to incorporate set-valued side information into models that scale to large numbers of items and attributes. In addition, existing recommendation models that leverage item attributes (e.g., content-based matrix factorization) are not directly tied to evaluation metrics. We developed RFS, a class of scalable recommendation models for items with attributes. Theoretically, we showed that optimizing the RFS objective optimizes recall and that RFS can approximate permutation invariant recommendation models including content-based matrix factorization. Empirically, models in the RFS class outperform competing models and scale to large datasets, such as our motivating problem of meal recommendation for 55k users who consume 16M meals.

How well does binary classification perform for other ranking-based recommendation metrics, such as nondiscounted cumulative gain? Analyzing this question is more difficult, and we leave this to future work. For generalization theory, we conjecture that a different loss function should allow a similar proof to Proposition 1. With sufficient data, RFS can learn arbitrary distributions of users consuming items with attributes. But performance on finite data can vary, and developing generalization theory for RFS remains an open question.

Finally, Bansal et al. (2020) compare RFS to a state-of-the-art model, BERT (Devlin et al. 2019), and find that it is faster to train and performs better on a document recommendation task. Characterizing why RFS performs better than BERT in terms of recall and computational speed may yield further improvements in future work.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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