Multi-Session Diversity to Improve User Satisfaction in Web Applications
Authors’ Copy

Mohammadreza Esfandiari
New Jersey Institute of Technology
Newark, NJ, USA
me76@njit.edu

Ria Mae Borromeo
University of the Philippines
Laguna, Philippines
riamae@gmail.com

Septideh Nikookar
New Jersey Institute of Technology
Newark, NJ, USA
sn627@njit.edu

Paras Sakharkar
New Jersey Institute of Technology
Newark, NJ, USA
ps863@njit.edu

Sihem Amer-Yahia
CNRS, Univ. Grenoble Alpes
Grenoble, France
sihem.amer-yahia@univ-grenoble-alpes.fr

Senjuti Basu Roy
New Jersey Institute of Technology
Newark, NJ, USA
senjuti.basuroy@njit.edu

Abstract
In various Web applications, users consume content in a series of sessions. That is prevalent in online music listening, where a session is a channel and channels are listened to in sequence, or in crowdsourcing, where a session is a set of tasks and task sets are completed in sequence. Content diversity can be defined in more than one way, e.g., based on artists or genres for music, or on requesters or rewards in crowdsourcing. A user may prefer to experience diversity within or across sessions. Naturally, intra-session diversity is set-based, whereas, inter-session diversity is sequence-based. This novel multi-session diversity gives rise to four bi-objective problems with the goal of minimizing or maximizing inter and intra diversities. Given the hardness of those problems, we propose to formulate a constrained optimization problem that optimizes inter diversity, subject to the constraint of intra diversity. We develop an efficient algorithm to solve our problem. Our experiments with human subjects on two real datasets, music and crowdsourcing, show our diversity formulations do serve different user needs, and yield high user satisfaction. Our large data experiments on real and synthetic data empirically demonstrate that our solution satisfy the theoretical bounds and is highly scalable, compared to baselines.

CCS Concepts
• Information systems → Crowdsourcing.

1 Introduction
Online content consumption is usually organized into sessions. That is prevalent in a variety of applications such as online music listening where users organize songs into channels and listen to a few songs within the same channel before switching to the next channels to listen to other artists in the same genre, or to experience different music styles. In crowdsourcing platforms, workers complete a small set of tasks at a time (session) and sequences of sessions within a finite time (for example, half a day). Diversifying content inside (intra) and across (inter) sessions is natural for such applications to improve user satisfaction and engagement. In this paper, we define multi-session diversity and study its impact on user satisfaction in Web applications. To the best of our knowledge, our work is the first attempt to combine set and sequence diversities, two problems extensively studied individually in search and recommendation [3, 7, 12, 17, 22, 23, 26, 29–31, 34, 37–40].

Creating playlists to listen to during a long-drive may need to minimize both intra and inter-session diversities to generate songs by the same artist within a channel and similar beats across channels. Contrarily, designing playlists for a theme party is best done by composing songs from the same period within a channel (90’s, 60’s, etc) and different styles across channels (by minimizing intra diversity on release date within a session and maximizing inter diversity on style across sessions). Similarly, in crowdsourcing, it may be ideal to assign tasks requiring similar skills within a session and different completion times across sessions. More generally, applications may require minimization or maximization of intra and inter diversities. Therefore, multi-session diversity aims to generate k sessions to a user, with a small number l of relevant items in each, yielding a total of N = k × l items. Intra and inter-session diversities can be either minimized or maximized which gives rise to 4 bi-objective problem variants.

Due to their hardness, we propose to formulate our 4 problems as a constrained optimization problem, with the goal of obtaining one point from the Pareto front (Section 2.2). The idea is to optimize inter diversity, subject to constraining intra diversity. There exists more than one benefit to this approach. First, in one of the two cases (i.e., minimization), Intra is tractable and easier to solve. Therefore,
finding the optimal constraint value is computationally efficient. More importantly, the constrained optimization problem aims at finding one point in the Pareto front, which is perfectly acceptable, as the points in the Pareto front are qualitatively indistinguishable. We design an efficient algorithm to solve this problem. We design algorithms with provable guarantees for intra and inter problems individually and together (Section 3).

We conduct four large-scale experiments: two with human subjects (music playlist and task recommendation), the other two with real and simulated data. In music recommendation (Section 4.1), our results highlight, with statistical significance, that user satisfaction than a baseline with no diversity. We investigate the idea is to optimize inter diversity, subject to the constraint of intra diversity. The diversity of items between two consecutive sessions is referred to as Inter and is defined for two consecutive sessions for a dimension $d$ as follows:

$$\text{Inter}^d(s_i, s_{i+1}) = (\mu_d^s - \mu_d^{s_{i+1}})^2 \tag{2}$$

which captures the difference between the average of two consecutive sessions. Given $S = \{t_1, t_2, t_3, \ldots, t_k\}$, $\text{Inter}^\text{Reward}(S) = (0.34 - 0.43)^2 + (0.433 - 0.35)^2 = 0.015$ using Example 1.

Other set-based [3] and sequence-based [40] definitions exist which captures the difference between the average of two consecutive sessions. Given $S = \{t_1, t_2, t_3, \ldots, t_k\}$, $\text{Inter}^\text{Reward}(S) = (0.34 - 0.43)^2 + (0.433 - 0.35)^2 = 0.015$ using Example 1.

Finally, we also observe that our approach is faster and highly scalable when varying the number of items and the number of sessions considering different data distributions.

## 2 Data Model and Diversity Problem

We describe a simple running example in crowdsourcing.

| Task | Skill | Reward | Task | Skill | Reward | Task | Skill | Reward |
|------|-------|--------|------|-------|--------|------|-------|--------|
| $t_1$ | 0.5   | 0.3    | $t_2$ | 0.51  | 0.4    | $t_3$ | 0.54  | 0.49   |
| $t_4$ | 0.59  | 0.5    | $t_5$ | 0.6   | 0.23   | $t_6$ | 0.63  | 0.4    |
| $t_7$ | 0.69  | 0.1    | $t_8$ | 0.7   | 0.60   | $t_9$ | 0.79  | 0.36   |
| $t_{10}$ | 0.8  | 0.12   | $t_{11}$ | 0.89 | 0.55   | $t_{12}$ | 0.93 | 0.34   |

### Table 1: Task Skill and Reward

**Example 1.** Consider a set of $N = 12$ tasks, which are most relevant to a specific worker. Table 1 shows two dimensions of these tasks. The first dimension is the skill requirement of the task as provided by the requester. The second dimension is the task reward. We want to generate 4 ($k$) sessions, each containing 3 ($l$) tasks.

### 2.1 Data Model

#### Item

An item has a set of dimensions. $t_d^i$ represents the $d$-th dimension of the $i$-th item. Using Example 1, task $t_1$ is represented by two dimensions, $<0.5, 0.30>$. In the case of a song, examples of dimensions are artist, vibe, genre, etc.

#### Session

A session $s$ consists of a set of $l$ items that can be consumed in any order.

#### Sequence

A sequence of sessions is an ordering of $k$ sessions $S = \{s_1, s_2, \ldots, s_k\}$ where sessions are presented to a user one after another.

#### Intra-Diversity

Given a dimension $d$, the diversity of a set of items in a single session $s$ is referred to as Intra and defined by capturing how each item in that session deviates from the average, considering $d$, and taking an aggregate over $l$ items as follows:

$$\text{Intra}^d(s) = \frac{1}{l} \sum_{i=1}^{l} (t_d^i - \mu_d^s)^2 \tag{1}$$

where $t_d^i$ is the value of dimension $d$ of item $t_i$ and $\mu_d^s$ is the average of $d$ values of items in session $s$. Intra essentially captures variance of a set of items for a dimension $d$. Following Example 1, if the session $s_1$ consists of $\{t_1, t_2, t_3\}$, then $\text{Intra}^\text{Skill}(s_1) = 0.005$.

#### Inter-Diversity

The diversity of items between two consecutive sessions is referred to as Inter and is defined for two consecutive sessions for a dimension $d$ as follows:

$$\text{Inter}^d(s_i, s_{i+1}) = (\mu_d^s - \mu_d^{s_{i+1}})^2 \tag{2}$$

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Full proofs will be made available in a deanonymized report.

### 3 Optimization Algorithms

We design optimization algorithms for the intra and inter problems individually, following which, we study how to solve the constrained optimization problem (Equation 3). Table 2 summarizes our technical results.
We study Min Intra where the objective is to generate $k$ sessions, each of length $l$, such that their aggregated Intra diversity is minimized. Specifically, if there are $l$ items associated with a dimension in a session, the intra diversity is the variance of those points. With an abstract representation, once sorted, the dimension values of $N$ items, fall on a line. Therefore, if the aggregated variance is to be minimized, it is intuitive that the sessions need to be formed by grouping $l$ values that are closest to each other. Thus we propose algorithm Ex-Min-Intra that first sorts the values of a dimension of interest. After that, it starts from the smallest value and forms a session. This algorithm produces an exact solution.

We now turn to Max Intra, an NP-hard problem. To maximize the Intra, we need to form the $k$ sessions in such a way that the means of all the sessions are equal or very close to each other. Algorithm Ap-Max-Intra is iterative and greedy and creates sessions that satisfy this property. First, it creates $l$ bins, each has $k$ different slots. Then, these bins are initialized in such a way that each bin contains a subset of $k$ items from the set of items. The final two steps run in an iterative manner. In the third step, the algorithm scores the bins as follows:

$$d(b_i) = \max(\frac{1}{N} \sum_{j \neq j} |\mu_{\text{global}} - \arg \max_j b_{ij}|, \frac{1}{N} \sum_{j \neq j} |\mu_{\text{global}} - \arg \min_j b_{ij}|)$$

, where $\mu_{\text{global}}$ is the global mean over all items. Finally, it greedily merges two bins. This process is repeated for $l - 1$ number of iterations.

To illustrate the solution further, $b_{ij}$ represents the $j$-th slot in bin $i$, which is kept as a placeholder for $l$-th session. To initialize the bins, we first sort the items in an increasing order on the dimension $i$. Next, in the $i$-th bin $1 \leq i \leq l$, we put the sorted items $t_{(i,k+1)}$ in bin $i$. Using Example 1, this amounts to creating 3 bins of tasks where $b_1 = \{ \{t_1, t_2, t_3, t_4\}\}, b_2 = \{ \{t_5, t_6, t_7\}\}, b_3 = \{ \{t_8, t_9\}\}$. In step 3, each bin is scored based on $d(b_i)$. Then two bins $i$ and $j$ are merged that have the largest and smallest score respectively. Going back to the Example 1, the scores are calculated as follows $d(b_1) = 0.18, d(b_2) = 0.08$, and $d(b_3) = 0.25$ and $b_2$ and $b_3$ are merged.

To merge $b - i$ with $b_j$, where $b - i$ has the largest score and $b_j$ has the smallest score, we create a new bin $b_{\text{merge}}$ that contains the $m$-th smallest items of $b_i$ and $m$-th largest items of $b_j$ ($1 \leq m \leq k$). Considering Example 1, the new bin $b_{\text{merge}}$ is created by combining $b_2$ and $b_3$, such that

$$b_{\text{merge}} = \{ \{t_5, t_{12}\}, \{t_6, t_{11}\}, \{t_7, t_{10}\}, \{t_8, t_9\}\}$$

This process is then repeated until only a single bin is left.

| Algorithm | Running Time | Approx Factor |
|-----------|--------------|---------------|
| Ex-Min-Intra | $O(N \log N)$ | Exact |
| Ap-Max-Intra | $O(N \log N + N!)$ | $\frac{1}{2}$ |
| Ap-Min-Inter | $O(N \log N + k^2 + \log k)$ | $4 - 2/k$ |
| Ap-Max-Inter | $O(N \log N + k^2 + \log k)$ | $1/2$ |

**Table 2: Optimization Algorithms and Results**

### 3.1 Algorithm Min(Max)-Intra

We study Min Intra where the objective is to generate $k$ sessions, each of length $l$, such that their aggregated Intra diversity is minimized. Specifically, if there are $l$ items associated with a dimension in a session, the intra diversity is the variance of those points. With an abstract representation, once sorted, the dimension values of $N$ items, fall on a line. Therefore, if the aggregated variance is to be minimized, it is intuitive that the sessions need to be formed by grouping $l$ values that are closest to each other. Thus we propose algorithm Ex-Min-Intra that first sorts the values of a dimension of interest. After that, it starts from the smallest value and finds each consecutive $l$ points to form a session. This algorithm produces an exact solution.

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, where $\mu_{\text{global}}$ is the global mean over all items. Finally, it greedily merges two bins. This process is repeated for $l - 1$ number of iterations.

To illustrate the solution further, $b_{ij}$ represents the $j$-th slot in bin $i$, which is kept as a placeholder for $l$-th session. To initialize the bins, we first sort the items in an increasing order on the dimension $i$. Next, in the $i$-th bin $1 \leq i \leq l$, we put the sorted items $t_{(i,k+1)}$ in bin $i$. Using Example 1, this amounts to creating 3 bins of tasks where $b_1 = \{ \{t_1, t_2, t_3, t_4\}\}, b_2 = \{ \{t_5, t_6, t_7\}\}, b_3 = \{ \{t_8, t_9\}\}$. In step 3, each bin is scored based on $d(b_i)$. Then two bins $i$ and $j$ are merged that have the largest and smallest score respectively. Going back to the Example 1, the scores are calculated as follows $d(b_1) = 0.18, d(b_2) = 0.08$, and $d(b_3) = 0.25$ and $b_2$ and $b_3$ are merged.

To merge $b - i$ with $b_j$, where $b - i$ has the largest score and $b_j$ has the smallest score, we create a new bin $b_{\text{merge}}$ that contains the $m$-th smallest items of $b_i$ and $m$-th largest items of $b_j$ ($1 \leq m \leq k$). Considering Example 1, the new bin $b_{\text{merge}}$ is created by combining $b_2$ and $b_3$, such that

$$b_{\text{merge}} = \{ \{t_5, t_{12}\}, \{t_6, t_{11}\}, \{t_7, t_{10}\}, \{t_8, t_9\}\}$$

This process is then repeated until only a single bin is left.

### 3.2 Algorithm Min(Max)-Inter

Optimization of Inter diversity, both minimization and maximization variants, is NP-hard, and they bear remarkable similarity to each other. Given a set of $N$ items, the Min(Max)-Inter problems will try to find an ordering of $k$ sessions, each with $l$ items, such that the aggregated differences between the means of two consecutive sessions is minimized (maximized). To better understand these problems, we break them into two steps. We only present these steps for the Max-Inter problem and note that the Min-Inter version works analogously, only by inverting the optimization goals inside the algorithm.

Our proposed solution Ap-Max-Inter for Max-Inter works as follows: we first find $k$ sessions obtained by running Algorithm Ap-Min-Intra. This is needed, since it will generate sessions with means as different from each other as possible. After that, we create a graph of $k$ nodes, each represents one of the $k$ sessions. The weight of each edge $(s_i, s_j)$ is defined as $w(s_i, s_j) = (\mu_{s_i} - \mu_{s_j})^2$ where $\mu_{s_i}$ (resp. $\mu_{s_j}$) is the mean of session $s_i$ (resp. $s_j$). After that, the goal is to run an algorithm for the Longest path problem for Max-Inter. Since the graph is complete with positive weights on the edges, the Longest Path Problem could be solved by replacing the positive weights with negative values and running a traveling salesman problem (TSP) over it. In our implementation, we use the simple yet effective 2-approximation algorithm for TSP in metric space, described in [25, 28]. The algorithm starts by finding the Minimum Spanning Tree of the input graph using Prim’s algorithm. Next, it lists the nodes in Minimum Spanning Tree in a pre-order walk and adds the edge to the starting vertex to the end. This path will create an ordering of sessions by following from the starting vertex $s_i$ to the ending vertex $s_j$. This algorithm runs in $O(k^2 \log k)$ which is dominated by the running time of the Prim’s algorithm. We further improve this running time by using Fibonacci heaps and obtain $O(k^2 + \log k)$.

Using Example 1 to find Max-Inter of Skill dimension, we first apply the Ex-Min-Intra to find the following sessions, $s_1 = \{t_1, t_2, t_3\}$, $s_2 = \{t_4, t_5, t_6\}$, $s_3 = \{t_7, t_8, t_9\}$, and $s_4 = \{t_{10}, t_{11}, t_{12}\}$ where $\mu_{s_1} = 0.516$, $\mu_{s_2} = 0.6066$, $\mu_{s_3} = 0.726$, and $\mu_{s_4} = 0.873$. These sessions will become 4 nodes of a complete graph. The nodes of this graph are the sessions and the weight of each edge is the Inter value we get from Equation 2. We solve the longest path problem for this
We validate how multi-session diversity improves user satisfaction and remove the edge. We observe how diversity affects user satisfaction in different contexts.

**Dataset.** The dataset consists of 727 songs from 54 albums, 47 artists, and 10 genres. The songs are from albums that won the Grammy Best Album of the Year Award between 1961 and 2020. The list of albums and their corresponding genres are from Wikipedia while the other information such as artist, period, popularity, tempo, and duration are from Spotify.

**Experiments Flow.** We first collect preferred genres and artists from users to form their profiles. We then generate 5 music playlists for each user. Each playlist has 5 channels, and each channel has 10 songs. The first 4 playlists are generated using the algorithms in Table 3, with dimensions specified for each context in Table 4. The 5th playlist represents the baseline with no diversity. It consists of similar songs randomly selected from one of the dimensions. In this last experiment, all songs from the period 2000’s. Lastly, users evaluate the playlists by selecting songs they would actually listen to, rating how much they like diversity in the sessions, and providing an overall rating of the playlist. The ratings are based on a 5-pf Likert scale where 1 is the lowest and 5 is the highest. We measure user satisfaction using the overall rating provided by users. We recruit 200 workers (50 per context) from Amazon Mechanical Turk (AMT). We pay workers $0.10 for profile collection and $1.00 for their evaluations.

### Summary of Results
We observe in Table 5 that user satisfaction in diversified playlists (Scenarios 1 – 4) is higher compared to the no-diversity baseline. This observation is statistically significant at p = 0.10 using a one-way Analysis of Variance (ANOVA) [32]. The results are consistent with other measures: workers select the smallest number of songs from the no-diversity playlist and the no-diversity playlist receives the lowest average diversity ratings. Moreover, these observations extend to different contexts, as shown in Table 6. The sample size of 200 workers from the estimated 200,000 workers in AMT [14] gives our results a 99% confidence level and a 10% error margin (based on the Central Limit Theorem [33]). In summary, our music experiment clearly shows that diversity is preferred over no diversity. Additionally, diversity definitions depend on context, as observed in Table 6.

### 4.1.1 Music Recommendation
We validate how multi-session diversity improves user satisfaction and consider different contexts namely music for long drive, theme party, Sunday morning, and learning a new music style, to observe how diversity affects user satisfaction in different contexts.

#### 4.1.2 Task Recommendation
In these experiments, we recommend short and long task sessions to workers in crowdsourcing. The short sessions consist of 3 sets each with 3 tasks. The long sessions consist of 5 sets and each set consists of 10 tasks.

#### Dataset
The dataset consists of 20,000 tasks from Figure Eight’s open data library [1]. Each task belongs to one of 10 types such as tweet classification, image transcription, and sentiment analysis. Each task type is represented as a set of keywords that best...
We again used a one-way ANOVA to evaluate statistical significance. To measure quality, we use the answers obtained from the workers. To measure quality, we use the answers obtained from the workers.

In short sessions, only throughput is statistically significant at \( p = 0.01 \) and worker satisfaction for short and long sessions in Table 7.

### Summary of Results

We present the average throughput, quality, and worker satisfaction for short and long sessions in Table 7.

Similarly to the music experiments, our sample size (n=200) allows our results to achieve 99% confidence level with 10% margin of error. We again used a one-way ANOVA to evaluate statistical significance. In short sessions, only throughput is statistically significant at \( p = 0.05 \). In long sessions, both quality and worker satisfaction are statistically significant at \( p = 0.10 \). Our results indicate that short sessions generated by our algorithms do not significantly differ from the no-diversity baseline in terms of quality and worker satisfaction. On the other hand, the throughput of no-diversity is significantly higher than sessions generated by our algorithms. This observation confirms previous studies where workers get more proficient in completing similar (and hence not diverse) tasks, allowing them to become faster at task completion [15]. As the number of tasks per session increases (long sessions) however, this observation changes. Throughput decreases for no-diversity and sessions generated by our algorithms obtain higher quality and worker satisfaction with statistical significance. In summary, our experiments show that the benefit of diversity in task recommendation is more prominent for sessions comprising many tasks. Diversity tends to bring positive effect to avoid boredom which is prominent for sessions with many tasks.

### 4.2 Large Data Experiments

The goal here is to evaluate our algorithms with appropriate baselines (including exact solutions) and compare them qualitatively (approximation factors, objective function value) and scalability-wise (running time). All algorithms are implemented in Python 3.6 on a 64-bit Windows server machine, with Intel Xeon Processor, and 16 GB of RAM. All numbers are presented as the average of five runs. For brevity we present a subset of results that are representative.

#### 4.2.1 Data Sets

* a. 1-Million Song: We use the Million Songs Dataset [2, 9] that has 1 million songs (please note the Spotify dataset used in Section 4.1 is small in scale). We have normalized the data to be between [0, 1]. This dataset also includes artist popularity and hotness, genre, release date and etc. The presented results are representative and consider tempo and loudness as dimensions.

* b. Synthetic dataset: The presented results on this are the ones that vary distributions of the underlying dimensions. We sample from three distributions: Normal, Uniform, and Zipfian. For Normal distribution, data is sampled with mean and standard deviation, \( \mu = 250, \sigma = 10 \). For Uniform, dataset is sampled from Uniform distribution between [0,500], and for Zipfian distribution default exponent is set to \( \alpha = 1.01 \). We produce a pool of \( 2^{30} \) items for each of our three distributions.

#### 4.2.2 Implemented Baselines

In addition to Random where we generate random sequences, we implement different baselines and compared the performance of our algorithms.

* **Optimal.** The optimal baseline is based on an Integer Programming (IP) algorithm that solves the problem optimally on small instances. The rationale behind implementing IP is to verify the theoretical approximation factors of our algorithms against the optimal solution. We used Gurobi as the solver.

* **Baseline-MMR.** This baseline is inspired by the MMR algorithm [10] used in diversifying web search results. MMR takes a search query and returns relevant and diverse results. Hence, our mapping to MMR optimizes intra-session diversity only. At each iteration, Baseline-MMR considers an item to be included or not in the result and calculates two scores: the *Intra* score of adding a new item to a session and the *max* (resp., *min* *Inter*) score of a new session to all other sessions in the case of *Max-Inter* (resp., *Min-Inter*). It then picks the highest or the lowest weighted sum of these two scores based on the *Intra* part of the problem. The item with that score is chosen to be added to the session. This process is repeated until there is no item left.

* **Clustering Algorithms are not applicable to be used as baselines** since they do not control session size, and they are not adapted to sequences.

#### 4.2.3 Summary of Results

**Overall, for our problems, where both Intra and Inter diversity are to be optimized, our algorithms are the unanimous choice considering both quality and scalability.**

When the Intra and Inter diversity is studied individually, our algorithms outperform all the baselines and empirically produce approximation factors close to 1, across varying \( k, N \), and different distributions. The only exception to this latter observation is Baseline-MMR.

### Table 5: Average evaluation scores across all contexts

| Scenario    | No. of Selected Songs | Diversity Rating | User Satisfaction |
|-------------|------------------------|-------------------|-------------------|
| 1 Min-Intra, Min-Inter | 13.16                  | 3.57              | 3.54              |
| 2 Min-Intra, Max-Inter   | 15.05                  | 3.66              | 3.66              |
| 3 Max-Intra, Min-Inter   | 14.71                  | 3.59              | 3.71              |
| 4 Max-Intra, Max-Inter   | 14.66                  | 3.69              | 3.71              |
| 5 no diversity          | 12.83                  | 3.35              | 3.44              |

The presented results on this are the ones that vary distributions of the underlying dimensions. We sample from three distributions: Normal, Uniform, and Zipfian. For Normal distribution, data is sampled with mean and standard deviation, \( \mu = 250, \sigma = 10 \). For Uniform, dataset is sampled from Uniform distribution between [0,500], and for Zipfian distribution default exponent is set to \( \alpha = 1.01 \). We produce a pool of \( 2^{30} \) items for each of our three distributions.

[10] used in diversifying web search results.

Baseline-MMR. This baseline is inspired by the MMR algorithm [10] used in diversifying web search results. MMR takes a search query and returns relevant and diverse results. Hence, our mapping to MMR optimizes intra-session diversity only. At each iteration, Baseline-MMR considers an item to be included or not in the result and calculates two scores: the *Intra* score of adding a new item to a session and the *max* (resp., *min* *Inter*) score of a new session to all other sessions in the case of *Max-Inter* (resp., *Min-Inter*). It then picks the highest or the lowest weighted sum of these two scores based on the *Intra* part of the problem. The item with that score is chosen to be added to the session. This process is repeated until there is no item left.

#### 4.2.2 Implemented Baselines

In addition to Random where we generate random sequences, we implement different baselines and compared the performance of our algorithms.

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* **Baseline-MMR.** This baseline is inspired by the MMR algorithm [10] used in diversifying web search results. MMR takes a search query and returns relevant and diverse results. Hence, our mapping to MMR optimizes intra-session diversity only. At each iteration, Baseline-MMR considers an item to be included or not in the result and calculates two scores: the *Intra* score of adding a new item to a session and the *max* (resp., *min* *Inter*) score of a new session to all other sessions in the case of *Max-Inter* (resp., *Min-Inter*). It then picks the highest or the lowest weighted sum of these two scores based on the *Intra* part of the problem. The item with that score is chosen to be added to the session. This process is repeated until there is no item left.

* **Clustering Algorithms are not applicable to be used as baselines** since they do not control session size, and they are not adapted to sequences.
Table 6: Average number of selected songs, average diversity rating, and average user satisfaction per context

| Scenario                | Long Drive | Theme | Sunday | Learn |
|-------------------------|------------|-------|--------|-------|
| 1. Min-Intra, Min-Inter | 16,583.64,3.62 | 14,86,3.52,3.88 | 14,76,3.64,3.34 | 14,42,3.46,3.32 |
| 2. Min-Intra, Max-Inter | 15,82,3.70,3.76 | 15,06,3.50,3.72 | 14,12,3.82,3.66 | 15,20,3.61,3.50 |
| 3. Max-Intra, Min-Inter | 16,52,3.70,3.86 | 15,64,3.54,3.98 | 14,30,3.58,3.56 | 14,38,3.54,3.44 |
| 4. Max-Intra, Max-Inter | 16,24,3.84,3.76 | 15,96,3.68,3.80 | 15,04,3.58,3.70 | 15,40,3.64,3.58 |
| 5. no diversity         | 14,10,3.34,3.60 | 12,92,3.30,3.42 | 13,62,3.46,3.46 | 11,68,3.30,3.28 |

Table 7: Task recommendation for short (first number) and long sessions (second number)

| Scenario                | Throughput | Quality (%) | Worker Satisfaction |
|-------------------------|------------|-------------|---------------------|
| 1. Min-Intra(date), Min-Inter(skill) | 6.13,6.95 | 65.64,68.33 | 4.47,4.48 |
| 2. Min-Intra(skill), Max-Inter(reward) | 5.93,6.96 | 62.77,69.27 | 4.43,4.5 |
| 3. Max-Intra(skill), Min-Inter(reward) | 5.91,6.96 | 61.76,70.08 | 4.44,4.41 |
| 4. Max-Intra(duration), Max-Inter(skill) | 5.33,6.98 | 61.24,67.98 | 4.46,4.40 |
| 5. no diversity         | 7.53,6.56 | 64.38,66.04 | 4.28,4.19 |

Table 8: Approximation factors on 1-Million Songs Dataset

| Scenario                | N=8192, k=16 | N=1024, k=128 |
|-------------------------|--------------|---------------|
| Intra                   | Inter        | Intra         | Inter        |
| Min-Intra, Min-Inter    | 1            | 1.05          | 1            |
| Max-Intra, Min-Inter    | 1            | 0.35          | 0.49         |
| Max-Intra, Max-Inter    | 0.99         | 1.06          | 0.98         |
| Min-Intra, Max-Inter    | 0.99         | 0.58          | 0.95         |

Table 7: Intra which performs better in maximizing Inter diversity (while performing very poorly for Intra optimization), which is due to its focus on optimizing inter-diversity only. Moreover, our algorithms are highly scalable and is much more efficient than the baselines.

4.2.4 Quality Evaluation. We vary k (the number of sessions), N (the number of items), and the data distribution. The default values are \( N=2^{13} \) and \( k=2^1 \) with a uniform distribution.

Comparison against Optimal. Table 8 shows the approximation factors for our algorithms for two default settings: \( (N=2^{13}, k=2^4) \) and \( (N=2^{10}, k=2^7) \) using 1-Million dataset. We can see that our algorithms produce an approximation factor equal to 1 when Intra diversity is minimized and a factor very close to 1 when Intra diversity is maximized.

When Inter diversity is minimized, the resulting approximation factors are close to 1. However, when Inter diversity is maximized, the approximation factors are slightly low as our algorithm solves the Intra part of the problem before ordering the sessions to maximize Inter diversity. It is hence bound by the constraints of the solution to Intra. Nevertheless, the solution formulated by our algorithm for Min-Intra,Max-Inter and Min-Intra,Min-Inter is able to produce a point on the Pareto Front in the optimal solution region which meets both the Intra and Inter objectives. The synthetic dataset mimics this trend as well.

Based on the approximation factor results and the above analysis, we conclude that our algorithms produce good and in some cases the best possible solution for the 4 problems we attempt to optimize.

Varying N. Figure 1 shows how Inter scores change as we vary N from \( 2^9 \) to \( 2^{16} \) for Baseline-MMR, Random and our algorithms. We have omitted the plots for Synthetic data experiments since those results closely follow the result for 1-Million Songs dataset. Figures 1(a)(c) confirms that our algorithm performs best when Inter diversity is minimized. The objective function improves with increasing N. On the other hand, as seen in Figures 1(b)(d), when Inter diversity is maximized, Baseline-MMR outperforms our algorithm with increasing N. This is because our algorithm is subject to the constraints imposed by optimizing Intra diversity first then maximizing the Inter diversity, while Baseline-MMR focuses on the Inter dimension only.

We also compare Intra scores whilst varying N. Table 9 showcases the approximation factors of our algorithm’s Intra considering Optimal for \( N \leq 2^{13} \) and \( N > 2^{13} \). A ratio of 1 means that the algorithm produces the best or optimal solution. These results showcase that our solutions achieve even better bound empirically compared to the theoretical bounds. Table 9 also shows that although Baseline-MMR performs better in Max-Inter problem, but it performs poorly for both Min-Intra and Max-Intra problems.

Interestingly, Random produces an approximation factor close to 1 for \( N > 2^{13} \) when maximizing Intra. This is because Intra is maximized when the variance of the sessions are maximized which is one of the side effects of Random. However, Baseline-MMR and Random produce very poor approximation factors when minimizing Intra. Contrarily, our solutions stay close to 1 approximation factor for both minimization and maximization of Intra diversity. As N increases, the Intra scores do not see any drastic change in approximation factors, and always stays close to 1.

Varying k. Figure 2 presents how Inter scores evolve as we vary k between \( 2^3 \) and \( 2^{11} \) for different baselines compared to our algorithm. We keep N constant at \( 2^{13} \). The synthetic dataset also mimics this trend. We observe figures 2(a)(c) that our algorithm performs significantly better than other baselines in maximizing Inter diversity. For Figures 2(b)(d), our observation is similar in the case of varying N. Baseline-MMR performs slightly better. Overall, Inter diversity increases for all 4 scenarios as k increases. This is because of the fact that when more sessions are present, it allows for more diversity between each session.
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Figure 1: Inter scores with varying $N$ for 1-Million Song dataset

Figure 2: Inter scores with varying $k$ for 1-Million Song dataset

The approximation factors of Intra, hold when varying $k$ (results omitted for space reasons).

| N       | Algorithms  |
|---------|-------------|
| $\leq 8192$ | MMR | Random | Ours |
| $0.008$  | 6.41E-05 | 1      |
| $>8192$  | $0.002$  | $5.42E-05$ | 1 |

Table 9: Intra approximation factors varying $N$ on 1-Million Song

Varying distribution. Figures 3 and 4 present how our algorithm and other baselines perform as we vary data distributions. We set $N$ to $2^{13}$ and $k$ to $2^7$.

Considering Intra scores, our algorithm performs the best using Uniform distribution for all 4 scenarios and using a Zipf distribution produces a similar trend. However, Normal performs slightly worse at times with our algorithm when we attempt to maximize Intra.

When we compare Inter scores, our algorithm performs best with Uniform distribution. In Figures 3(b)(d), Baseline-MMR outperforms our algorithm due to the same reasons mentioned in the varying $k$ and $N$ section of this paper.

We also observe that across all 4 scenarios, Zipf produces scores much larger in magnitude than Normal or Uniform distribution. This is due to the range of values in Zipf, which results in larger Intra and Inter scores. Overall, our algorithms stand out to be the best choice, with its best performance being on Uniform distribution.

4.2.5 Scalability Evaluation. We compare the running time of the three algorithms for 1-Million dataset.

In Figures 5, we vary $k$ and set $N$ to $2^{13}$. Naturally, as $N$ increases, the running time of our algorithms increases. We observe that our algorithms scale very well but are sometimes slightly slower than Random. This is unsurprising, as Random does not even have to do much work to generate sessions (recall that however it performs poorly qualitatively). However, with increasing values of $k$, our algorithms are consistently faster. We also observe that as we vary $N$ with $k = 2^7$, our algorithms are the fastest in all diversity scenarios (plots are omitted for space reasons).

Overall, we find that our algorithms are highly scalable and produce results within a few seconds for very large values of $N$ and $k$, while some of the baselines take hours to complete.

5 Related Work

Applications. Diversity has been extensively studied in recommendation and search applications [3, 7, 12, 17, 22, 23, 26, 29–31, 34, 36–40], to return items that are relevant as well as cover full range of users interests. The goal is to achieve a compromise between relevance and result heterogeneity. Existing works [20, 35] have also acknowledged the need for diversity and sequence based modeling in different recommendation applications. Recent works in crowdsourcing [18, 27] have demonstrated the importance of diversity in task recommendation. Task diversity is grounded in organization theories and has shown to impact the motivation of the workers [11]. Amer-Yahia et al. [6] propose the notion of composite tasks (CT),
Figure 3: Synthetic Data: Inter and Intra scores varying distributions

(a) Min-Intra, Min-Inter
(b) Min-Intra, Max-Inter
(c) Max-Intra, Min-Inter
(d) Max-Intra, Max-Inter

Figure 4: Synthetic Data: Zipf Distribution

(a) Min-Intra, Min-Inter
(b) Min-Intra, Max-Inter
(c) Max-Intra, Min-Inter
(d) Max-Intra, Max-Inter

Figure 5: Running times varying $k$ for 1-Million Song dataset

(a) Min-Intra, Min-Inter
(b) Min-Intra, Max-Inter
(c) Max-Intra, Min-Inter
(d) Max-Intra, Max-Inter

a set of similar tasks that match workers’ profiles, comply with their desired reward and task arrival rate. Their experiments show that diverse CTs contribute to improving outcome quality. A recent work has studied intra and inter-table influence in web table matching [18] involving crowd. Even though completing similar tasks lead to faster completion time [15], but such composition lead to fatigue and boredom, and task abandonment [13, 19, 21]. Aipe and Gadiraju [4] empirically observe that workers who perform similar tasks achieve higher accuracy and faster task completion time compared to workers who complete diverse tasks. However, they find that these workers experience fatigue the most. Alsayasneh et al. integrate the concept of diversity in composite tasks and empirically find a positive effect of diversity in outcome quality [5]. For all of these applications, diversity is studied set-based or sequence based only.

These applications call for a deeper examination of diversity and a powerful framework to capture its variants, which is our focus here.

Set and Sequence Diversities. Existing works on diversification could be classified as set-based only [3, 17, 26, 29, 30, 34] or sequence-based only [7, 12, 22, 40]. As an example, in [40], the authors study sequence-based diversity that is defined as the diversity of any permutation of the items. Another example is [7], in which taxonomies are used to sample search results to reduce homogeneity. In [3], the authors propose an algorithm with a provable approximation factor to find relevant and diverse news articles. In the database context, Chen and Li [12] propose to post-process
structured query results, organizing them in a decision tree for easier navigation. In [8, 24], the notion of diversity is used in the results of queries to produce closest results such that each answers is different from the rest. In recommender systems, results are typically post-processed using pair-wise item similarity to generate a list that achieves a balance between relevance and diversity. For example, in [16], recommendation diversity is formulated as a set-cover problem.

To the best of our knowledge, existing works have focused on achieving diversity in a single set. We solve set-based and sequence-based diversities in tandem and develop algorithms with guarantees.

6 Conclusion
We initiate the study of a scalable algorithmic framework and experimental studies to address multi-session diversity to improve user satisfaction in Web applications (from song playlists to task recommendations in crowdsourcing). The combination of Intra and Inter session diversities gives rise to four bi-optimization problems. We develop algorithms to solve our problems. Our extensive empirical evaluation, conducted using human subjects, as well as large scale real and simulated data, shows the need for diversity to improve user satisfaction and the superiority of our algorithms against multiple baselines.

This work opens up more than one research directions: an immediate extension of our work is to observe users as they consume recommendations in crowdsourcing. The combination of Inter and Intra recommendations in crowdsourcing). The combination of diversity in a single set. We solve set-based and sequence-based diversities in tandem and develop algorithms with guarantees.

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