Want to recommend movies based on user ratings for movies.

**Challenge:** Users have rated relatively few of the entire catalog.

Can think of this as a matrix of users and ratings with missing data!
Assume that each item has $k$ (unknown) features.

   e.g., $k$ possible genres of movies (action, romance, sci-fi, etc.)

Then, we can describe an item $v$ with feature vector $R_v$

   How much is the movie action, romance, sci-fi, ...

   e.g., $R_v = [0.3, \ 0.01, \ 1.5, \ ... ]$

We can also describe each user $u$ with a feature vector $L_u$

   How much they like action, romance, sci-fi, ....

   Example: $L_u = [2.3, \ 0, \ 0.7, \ ... ]$

Estimate rating for user $u$ and movie $v$ as

   $Rating(u, v) = L_u \cdot R_v = 2.3 \cdot 0.3 + 0 \cdot 0.01 + 0.7 \cdot 1.5 + ...$
Example

Suppose we have learned the following user and movie features using 2 features

<table>
<thead>
<tr>
<th>User ID</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2, 0)</td>
</tr>
<tr>
<td>2</td>
<td>(1, 1)</td>
</tr>
<tr>
<td>3</td>
<td>(0, 1)</td>
</tr>
<tr>
<td>4</td>
<td>(2, 1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Movie ID</th>
<th>Feature vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(3, 1)</td>
</tr>
<tr>
<td>2</td>
<td>(1, 2)</td>
</tr>
<tr>
<td>3</td>
<td>(2, 1)</td>
</tr>
</tbody>
</table>

Then we can predict what each user would rate each movie

\[
\begin{bmatrix}
2 & 0 \\
1 & 1 \\
0 & 1 \\
2 & 1 \\
\end{bmatrix} \times \begin{bmatrix}
3 & 1 & 2 \\
1 & 2 & 1 \\
\end{bmatrix} = \begin{bmatrix}
6 & 2 & 4 \\
4 & 3 & 3 \\
1 & 2 & 1 \\
7 & 4 & 5 \\
\end{bmatrix}
\]
Matrix Factorization

**Goal:** Find $L_u$ and $R_v$ that when multiplied, achieve predicted ratings that are close to the values that we have data for.

Our quality metric will be (could use others)

$$
\hat{L}, \hat{R} = \arg\min_{L,R} \sum_{u,v: r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2
$$
Unique Solution?

Is this problem well posed? Unfortunately, there is not a unique solution 😞

For example, assume we had a solution

\[
\begin{bmatrix}
6 & 2 & 4 \\
4 & 3 & 3 \\
1 & 2 & 1 \\
7 & 4 & 5
\end{bmatrix}
\quad = 
\begin{bmatrix}
2 & 0 &  \quad \\
1 & 1 &  \\
0 & 1 &  \\
2 &  & 1
\end{bmatrix}^{T}
\]

Then doubling everything in $L$ and halving everything in $R$ is also a valid solution. The same is true for all constant multiples.

\[
\begin{bmatrix}
6 & 2 & 4 \\
4 & 3 & 3 \\
1 & 2 & 1 \\
7 & 4 & 5
\end{bmatrix}
\quad = 
\begin{bmatrix}
4 & 0 &  \quad \\
2 & 2 &  \\
0 & 2 &  \\
4 & 2
\end{bmatrix}^{T}
\]
CSE/STAT 416
Recommender Systems: Matrix Factorization

Hunter Schafer
University of Washington
May 24, 2023

❓ Questions? Raise hand or sli.do #cs416
🎵 Listening to:
You have $n$ users and $m$ items in your system
- Typically, $n \gg m$. E.g., Youtube: 2.6B users, 800M videos

Based on the content, we have a way of measuring user preference. This data is put together into a user-item interaction matrix.

**Task:** Given a user $u_i$ or item $v_j$, predict one or more items to recommend.
Solution 0: Popularity

**Simplest Approach:** Recommend whatever is popular
Rank by global popularity (i.e., Squid Game)
Solution 1: Nearest User (User-User)

User-User Recommendation:

Given a user $u_i$, compute their $k$ nearest neighbors.

Recommend the items that are most popular amongst the nearest neighbors.
Solution 2: “People Who Bought This Also Bought…” (Item-Item)

Item-Item Recommendation:

Create a co-occurrence matrix $C \in \mathbb{R}^{m \times m}$ ($m$ is the number of items). $C_{ij} =$ # of users who bought both item $i$ and $j$.

For item $i$, predict the top-$k$ items that are bought together.
Normalizing Co-Occurrence Matrices

**Problem:** popular items drown out the rest!

**Solution:** Normalizing using Jaccard Similarity.

\[ S_{ij} = \frac{\text{# purchased } i \text{ and } j}{\text{# purchased } i \text{ or } j} = \frac{C_{ij}}{C_{ii} + C_{jj} - C_{ij}} \]

<table>
<thead>
<tr>
<th></th>
<th>Sunglasses</th>
<th>Baby Bottle</th>
<th>...</th>
<th>Diapers</th>
<th>Swim Trunks</th>
<th>Baby Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunglasses</td>
<td>1.00</td>
<td>0.03</td>
<td>...</td>
<td>0.02</td>
<td>0.23</td>
<td>0.04</td>
</tr>
<tr>
<td>Baby Bottle</td>
<td>0.03</td>
<td>1.00</td>
<td>...</td>
<td>0.09</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
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<td>0.09</td>
<td>...</td>
<td>1.00</td>
<td>0.04</td>
<td>0.08</td>
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<td>...</td>
<td>0.08</td>
<td>0.03</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Solution 3: Feature-Based
Solution 3: Feature-Based

What if we know what factors lead users to like an item?

**Idea:** Create a feature vector for each item. Learn a regression model!

<table>
<thead>
<tr>
<th>Genre</th>
<th>Year</th>
<th>Director</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>1994</td>
<td>Quentin Tarantino</td>
</tr>
<tr>
<td>Sci-Fi</td>
<td>1977</td>
<td>George Lucas</td>
</tr>
</tbody>
</table>

Define weights on these features for all users (global)

\[ w_G \in \mathbb{R}^d \]

Fit linear model
What if we know what factors lead users to like an item?

**Idea:** Create a feature vector for each item. Learn a regression model!

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<th>...</th>
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</tr>
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<td>Sci-Fi</td>
<td>1977</td>
<td>George Lucas</td>
<td>...</td>
</tr>
</tbody>
</table>

Define weights on these features for **all users** (global)

\[ w_G \in \mathbb{R}^d \]

Fit linear model

\[ \hat{r}_{uv} = w_G^T h(v) = \sum_i w_{G,i} h_i(v) \]

\[ \tilde{w}_G = \text{argmin}_w \frac{1}{\# \text{ratings}} \sum_{u,v: r_{uv} \neq ?} (w_G^T h(v) - r_{uv})^2 + \lambda \|w_G\| \]
Add user-specific features to the feature vector!

<table>
<thead>
<tr>
<th>Genre</th>
<th>Year</th>
<th>Director</th>
<th>...</th>
<th>Gender</th>
<th>Age</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Action</td>
<td>1994</td>
<td>Quentin Tarantino</td>
<td>...</td>
<td>F</td>
<td>25</td>
<td>...</td>
</tr>
<tr>
<td>Sci-Fi</td>
<td>1977</td>
<td>George Lucas</td>
<td>...</td>
<td>M</td>
<td>42</td>
<td>...</td>
</tr>
</tbody>
</table>
Personalization: Option B

Include a user-specified deviation from the global model.

\[ \hat{r}_{uv} = (\hat{w}_G + \hat{w}_u)^T h(v) \]

Start a new user at \( \hat{w}_u = 0 \), update over time.

- OLS on the residuals of the global model
- Bayesian Update (start with a probability distribution over user-specific deviations, update as you get more data)
Pros:
- No cold-start issue!
  - Even if a new user/item has no purchase history, you know features about them.
- Personalizes to the user and item.
- Scalable (only need to store weights per feature)
- Can add arbitrary features (e.g., time of day)

Cons:
- Hand-crafting features is very tedious and unscalable 😞
Solution 4: Matrix Factorization

Can we learn the features of items?
Assume that each item has \( k \) (unknown) features.

   e.g., \( k \) possible genres of movies (action, romance, sci-fi, etc.)

Then, we can describe an item \( v \) with feature vector \( R_v \)

   How much is the movie action, romance, sci-fi, ...

   e.g., \( R_v = [0.3, 0.01, 1.5, \ldots] \)

We can also describe each user \( u \) with a feature vector \( L_u \)

   How much they like action, romance, sci-fi, ....

   Example: \( L_u = [2.3, 0, 0.7, \ldots] \)

Estimate rating for user \( u \) and movie \( v \) as

\[
\text{Rating}(u, v) = L_u \cdot R_v = 2.3 \cdot 0.3 + 0 \cdot 0.01 + 0.7 \cdot 1.5 + \ldots
\]
Matrix Factorization Learning

**Goal:** Find $L_u$ and $R_v$ that when multiplied, achieve predicted ratings that are close to the values that we have data for.

Our quality metric will be (could use others):

$$\hat{L}, \hat{R} = \arg\min_{L,R} \frac{1}{\text{# ratings}} \sum_{u,v: r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2$$

This is the MSE, but we are learning both “weights” (how much the user likes each feature) and item features!
Why Is It Called Matrix Factorization?

Also called **Matrix Completion**, because this technique can be used to fill in missing values of a matrix.
Suppose we have learned the following user and movie features using 2 features

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Movie ID</th>
<th>Feature vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(3, 1)</td>
</tr>
<tr>
<td>2</td>
<td>(1, 2)</td>
</tr>
<tr>
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</tr>
</tbody>
</table>

What is the predicted rating user 1 will have of movie 2?
What is the highest predicted rating from this matrix factorization model? Which user made the prediction, for which movie?
Suppose we have learned the following user and movie features using 2 features

\[ \hat{r}_{u,v} = L_1 \cdot R_2 = 2 \cdot 1 + 0 \cdot 2 = 2 \]

What is the predicted rating user 1 will have of movie 2?

What is the highest predicted rating from this matrix factorization model? Which user made the prediction, for which movie?
Example

Suppose we have learned the following user and movie features using 2 features

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<td>(1, 2)</td>
</tr>
<tr>
<td>3</td>
<td>(2, 1)</td>
</tr>
</tbody>
</table>

Then we can predict what each user would rate each movie

\[
\begin{array}{ccc}
L & | & R^T \\
2 & 0 & 3 & 1 & 2 \\
1 & 1 & 1 & 2 & 1 \\
0 & 1 & 6 & 2 & 4 \\
2 & 1 & 4 & 3 & 3 \\
\end{array}

\begin{array}{ccc}
6 & 2 & 4 \\
4 & 3 & 3 \\
1 & 2 & 1 \\
7 & 4 & 5 \\
\end{array}
\]
Coordinate Descent
Remember, our quality metric is

$$\hat{L}, \hat{R} = \operatorname{argmin}_{L,R} \frac{1}{\# \text{ratings}} \sum_{u,v: r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2$$

Gradient descent is not used in practice to optimize this, since it is much easier to implement coordinate descent (i.e., Alternating Least Squares) to find $\hat{L}$ and $\hat{R}$.
**Coordinate Descent**

**Goal:** Minimize some function $g(w) = g(w_0, w_1, \ldots, w_D)$

Instead of finding optima for all coordinates, do it for one coordinate at a time!

Initialize $\hat{w} = 0$ (or smartly)

while not converged:
  pick a coordinate $j$
  $\hat{w}_j = \arg\min_w g(\hat{w}_0, \ldots, \hat{w}_{j-1}, w, \hat{w}_{j+1}, \ldots, \hat{w}_D)$

To pick coordinate, can do round robin or pick at random each time.

Guaranteed to find an optimal solution under some constraints
Coordinate Descent for Matrix Factorization

\[ \hat{L}, \hat{R} = \arg\min_{L,R} \frac{1}{\# \text{ratings}} \sum_{u,v:r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2 \]

Fix movie factors \( R \) and optimize for \( L \)

\[ \hat{L} = \arg\min_{L} \frac{1}{\# \text{ratings}} \sum_{u,v:r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2 \]

**First key insight:** users are independent!

\[ \hat{L}_u = \arg\min_{L_u} \frac{1}{\# \text{ratings for } u} \sum_{v:r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2 \]
Coordinate Descent for Matrix Factorization

\[ \hat{L}_u = \arg\min_{L_u} \frac{1}{\text{# ratings for } u} \sum_{v: r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2 \]

**Second key insight:** this looks a lot like linear regression!

\[ \hat{w} = \arg\min_w \frac{1}{n} \sum_{i=1}^{n} (w \cdot h(x_i) - y_i)^2 \]

**Takeaway:** For a fixed $R$, we can learn $L$ using linear regression, separately per user.

Conversely, for a fixed $L$, we can learn $R$ using linear regression, separately per movie.
Want to optimize

\[
\hat{L}, \hat{R} = \arg\min_{L,R} \frac{1}{\# \text{ratings}} \sum_{u,v : r_{uv} \neq ?} (L_u \cdot R_v - r_{uv})^2
\]

Fix movie factors \( R \), and optimize for user factors separately

**Step 1:** Independent least squares for each user

\[
\hat{L}_u = \arg\min_{L_u} \frac{1}{\# \text{ratings for } u} \sum_{v \in V_u} (L_u \cdot R_v - r_{uv})^2
\]

Fix user factors, and optimize for movie factors separately

**Step 2:** Independent least squares for each movie

\[
\hat{R}_v = \arg\min_{R_v} \frac{1}{\# \text{ratings for } v} \sum_{u \in V_v} (L_u \cdot R_v - r_{uv})^2
\]

Repeatedly do these steps until convergence (to local optima)

System might be underdetermined: Use regularization
Consider we had the ratings matrix

<table>
<thead>
<tr>
<th></th>
<th>Movie 1</th>
<th>Movie 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>4</td>
<td>?</td>
</tr>
<tr>
<td>User 2</td>
<td>?</td>
<td>2</td>
</tr>
</tbody>
</table>

During one step of optimization, user and movie factors are

<table>
<thead>
<tr>
<th>User Factors</th>
<th>Movie Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>Movie 1</td>
</tr>
<tr>
<td></td>
<td>Movie 2</td>
</tr>
<tr>
<td>[1, 2, 1]</td>
<td>[2, 1, 0]</td>
</tr>
<tr>
<td>User 2</td>
<td></td>
</tr>
<tr>
<td>[1, 1, 0]</td>
<td>[0, 0, 2]</td>
</tr>
</tbody>
</table>

Two questions:

**What is the current MSE loss?** (number)

Assume the next step of coordinate descent updates the user factors. Which factors would change?

- User 1
- User 2
- User 1 and 2
- None
Consider we had the ratings matrix

<table>
<thead>
<tr>
<th></th>
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<th>Movie 2</th>
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<tbody>
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Two questions:

What is the current MSE loss? (number)

Assume the next step of coordinate descent updates the user factors. Which factors would change?

- User 1
- User 2
- User 1 and 2
- None
Brain Break
What Has Matrix Factorization Learnt?

Matrix Factorization is a very versatile technique!

- Learns a latent space of topics that are most predictive of user preferences.
- Learns the “topics” that exist in movie $v$: $\hat{R}_v$
- Learns the “topic preferences” for user $u$: $\hat{L}_u$
- Predict how much a user $u$ will like a movie $v$
  \[
  \text{Rating}(u, v) = \hat{L}_u \cdot \hat{R}_v
  \]
Recommender Systems

**Recommendations**: (Semi-Supervised)

Use matrix factorization to predict user ratings on movies the user hasn’t watched

Recommend movies with highest predicted rating

<table>
<thead>
<tr>
<th>User</th>
<th>Movie</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><img src="Image" alt="Rating Stars" /></td>
</tr>
</tbody>
</table>

![Movie Ratings Table]
**Topic Modeling**: (Unsupervised)

Treat the TF-IDF matrix as the user-item matrix
- Documents are ”users”
- Words are “items”

$L$ tells us which topics are present in each document
$R$ tells us what words each topic is composed of

Oftentimes, the topics are interpretable!

**HW7 Programming: Tweet Topic Modeling**

$X_{ij}$ known for black cells
$X_{ij}$ unknown for white cells

Rows index movies
Columns index users

$X \approx X_L R' = \text{Application to text data:}$

```
party law
government
election court
president elected
council general minister
international political
council members
caucus

season team
game league games
player coach football
record fans head coach
second career play baseball
history three years marriage

school students
university college
education exam program
students admission

radio station news
television channel
broadcast stations network media
instreaming stream

index table
categories
list lookup

album band
song
release
music

white red
black blue
colored

war army
military force battle
force british
campaign
government warship
civilian world war one

age 18
population income
average years
median living in
mean

103 female
people families urban town
population inside

music musical opera
orchestra symphony
chamber symphony
```

```
```
Solution 4
(Matrix Factorization)
Pros / Cons

Pros:
- Personalizes to item and user!
- Learns latent features that are most predictive of user ratings.

Cons:
- Cold-Start Problem
  - What do you do about new users or items, with no data?
Common Issues with Recommender Systems

(and some solutions)
Recommender systems

Content based methods
Define a model for user-item interactions where users and/or items representations are given (explicit features).

Collaborative filtering methods

Model based
Define a model for user-item interactions where user and items representations have to be learned from interactions matrix.

Memory based
Define no model for user-item interactions and rely on similarities between users or items in terms of observed interactions.

Hybrid methods
Mix content based and collaborative filtering approaches.
Think

1 min

You are a software engineer at Spotify and have developed a matrix-factorization based recommendation system. The system works very well on existing users and songs, but does not work on new users or new songs.

How can you augment, extend, and/or modify your recommender system to handle new songs/users?
You are a software engineer at Spotify and have developed a matrix-factorization based recommendation system. The system works very well on existing users and songs, but does not work on new users or new songs.

How can you augment, extend, and/or modify your recommender system to handle new songs/users?
<table>
<thead>
<tr>
<th></th>
<th>Efficiency (Space, Deploy)</th>
<th>Efficiency (Time, Deploy)</th>
<th>Addresses Cold-Start?</th>
<th>Personalizes to User?</th>
<th>Discovers Latent Features?</th>
</tr>
</thead>
<tbody>
<tr>
<td>User-User</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Item-Item</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feature-Based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Matrix Factorization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

User-User: System that recommends items based on user-user similarities.

Item-Item: System that recommends items based on item-item similarities.

Feature-Based: System that recommends items based on feature-based methods.

Matrix Factorization: System that recommends items based on matrix factorization techniques.

Hybrid: System that combines feature-based and matrix factorization methods.
Featurized Matrix Factorization

**Feature-based approach**
- Feature representation of user and movie fixed
- Can address cold start problem

**Matrix factorization approach**
- Suffers from cold start problem
- User & Movie features are learned from data

**A unified model**
Cold-Start Problem

When a new user comes in, we don’t know what items they like! When a new item comes into our system, we don’t know who likes it! This is called the cold start problem.

Addressing the cold-start problem (for new users):

- Give random predictions to a new user.
- Give the globally popular recommendations to a new user.
- Require users to rate items before using the service.
- Use a feature-based model (or a hybrid between feature-based and matrix factorization) for new users.
Top-K versus Diverse Recommendations

Top-k recommendations might be very redundant
 Someone who likes Rocky I also will likely enjoy Rocky II, Rocky III, Rocky IV, Rocky V

Diverse Recommendations
 Users are multi-faceted & we want to hedge our bets
 Maybe recommend: Rocky II, Always Sunny in Philadelphia, Robin Hood

Solution: Maximal Marginal Relevance
 Pick recommendations one-at-a-time.
 Select the item that the user is most likely to like and that is most dissimilar from existing recommendations.
 - Hyperparameter $\lambda$ to trade-off between those objectives.
Users always get recommended similar content and are unable to discover new content they might like.

**Exploration-Exploitation Dilemma**
- Common problem in “online learning” settings

**Pure Exploration:** show users random content
- Users can discover new interests, but will likely be unsatisfied

**Pure Exploitation:** show users content they’re likely to like
- Users can’t discover new interests.

**Solution:** Multi-Armed Bandit Algorithms (beyond the scope of 416)
In the real-world, recommender systems guide us along a path through the content in a service.

If watch video 1, recommend video 2
If watch video 2, recommend video 3

A 2019 study found that YouTube's algorithms lead users to more and more radical content.

“Intellectual Dark Web” ➔ Alt-Lite ➔ Alt-Right
See more: iSchool 2021 Spring Lecture on Algorithmic Bias & Governance

Youtube’s response has been whack-a-mole. (Remove the content, manually tweak the recommendations for that topic)
TikTok

2021 experiment on time-to-seeing radical alt-right content

Source: https://www.tiktok.com/@tofology/video/7016081760643534085?lang=en
Evaluating Recommender Systems
It is possible to evaluate recommender systems using existing metrics we have learnt:

- MSE (if predicting ratings)
- Accuracy (if predicting like/dislike, or click/ignore)

However, we don’t really care about accurately predicting what a user won’t like.

Rather, we care about finding the few items they will like.

Instead, we focus on the following metrics:

How many of our recommendations did the user like?

How many of the items that the user liked did we recommend?

Sound familiar?
Precision and recall for recommender systems

\[
\text{precision} = \frac{\# \text{liked} \& \text{shown}}{\# \text{shown}} \quad \text{and} \quad \text{recall} = \frac{\# \text{liked} \& \text{shown}}{\# \text{liked}}
\]

What happens as we vary the number of recommendations we make?

Best Recommender System:
- **Top-1**: high precision, low recall
- **Top-k (large k)**: high precision, high recall

Average Recommender System:
- **Top-1**: average precision, low recall
- **Top-k (large k)**: low precision, high recall
Precision - Recall Curves
Comparing Recommender Systems

In general, it depends

What is true always is that for a given precision, we want recall to be as large as possible (and vice versa)

What target precision/recall depends on your application

One metric: area under the curve (AUC)

Another metric: Set desired recall and maximize precision (precision at k)
Recap

Now you know how to:

- Describe the input (observations, number of “topics”) and output ("topic" vectors, predicted values) of a matrix factorization model
- Implement a coordinate descent algorithm for optimizing the matrix factorization objective presented
- Compare different approaches to recommender systems
- Describe the cold-start problem and ways to handle it (e.g., incorporating features)
- Analyze performance of various recommender systems in terms of precision and recall
- Use AUC or precision-at-k to select amongst candidate algorithms