Recommender Systems: Latent Factor Models

Thanks to
Jure Leskovec, Anand Rajaraman, Jeff Ullman
http://www.mmds.org
The Netflix Prize

- **Training data**
  - 100 million ratings, 480,000 users, 17,770 movies
  - 6 years of data: 2000-2005

- **Test data**
  - Last few ratings of each user (2.8 million)
  - **Evaluation criterion**: Root Mean Square Error (RMSE) =
    $$\frac{1}{|R|} \sqrt{\sum_{(i,x) \in R} (\hat{r}_{xi} - r_{xi})^2}$$
  - Netflix’s system RMSE: 0.9514

- **Competition**
  - 2,700+ teams
  - **$1 million** prize for 10% improvement on Netflix
# The Netflix Utility Matrix $R$

The Netflix utility matrix $R$ is a large matrix that represents user preferences for movies. It contains ratings given by 480,000 users for 17,700 movies. Each cell in the matrix represents the rating a user gave to a movie. The matrix is shown below:

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The matrix is visualized with a box, where each cell is filled with the corresponding rating value.
**Utility Matrix $R$: Evaluation**

**Matrix $R$**

$$\text{RMSE} = \frac{1}{|R|} \sqrt{\sum_{(i,x) \in R} (\hat{r}_{xi} - r_{xi})^2}$$

- **480,000 users**
- **17,700 movies**

**Training Data Set**

**Test Data Set**

True rating of user $x$ on item $i$

Predicted rating

The winner of the Netflix Challenge!

Multi-scale modeling of the data:
Combine top level, “regional” modeling of the data, with a refined, local view:

- **Global:**
  - Overall deviations of users/movies
- **Factorization:**
  - Addressing “regional” effects
- **Collaborative filtering:**
  - Extract local patterns
Global:
- Mean movie rating: 3.7 stars
- *The Sixth Sense* is 0.5 stars above avg.
- Joe rates 0.2 stars below avg.
  \[\Rightarrow\text{Baseline estimation:}\]
  *Joe will rate *The Sixth Sense* 4 stars

Local neighborhood (CF/NN):
- *Joe* didn’t like related movie *Signs*
  \[\Rightarrow\text{Final estimate:}\]
  *Joe will rate* *The Sixth Sense* 3.8 stars
Recap: Collaborative Filtering (CF)

- Earliest and most popular **collaborative filtering method**
- Derive unknown ratings from those of “similar” movies (item-item variant)
- Define **similarity measure** $s_{ij}$ of items $i$ and $j$
- Select $k$-nearest neighbors, compute the rating
  - $N(i; x)$: items most similar to $i$ that were rated by $x$

$$
\hat{r}_{xi} = \frac{\sum_{j \in N(i; x)} s_{ij} \cdot r_{xj}}{\sum_{j \in N(i; x)} s_{ij}}
$$

$s_{ij}$… similarity of items $i$ and $j$
$r_{xj}$… rating of user $x$ on item $j$
$N(i; x)$… set of items similar to item $i$ that were rated by $x$
In practice we get better estimates if we model deviations:

\[ \hat{r}_{xi} = b_{xi} + \frac{\sum_{j \in N(i; x)} s_{ij} \cdot (r_{xj} - b_{xj})}{\sum_{j \in N(i; x)} s_{ij}} \]

Baseline estimate for \( r_{xi} \)

\[ b_{xi} = \mu + b_x + b_i \]

- \( \mu \) = overall mean rating
- \( b_x \) = rating deviation of user \( x \)
  = \( (\text{avg. rating of user } x) - \mu \)
- \( b_i \) = (avg. rating of movie \( i \)) – \( \mu \)

**Problems/Issues:**

1) Similarity measures are “arbitrary”
2) Pairwise similarities neglect interdependencies among users
3) Taking a weighted average can be restricting

**Solution:** Instead of \( s_{ij} \) use \( w_{ij} \) that we estimate directly from data
Use a **weighted sum** rather than **weighted avg.**:

\[
\hat{r}_{xi} = b_{xi} + \sum_{j \in N(i;x)} w_{ij}(r_{xj} - b_{xj})
\]

**A few notes:**

- \(N(i;x)\) ... set of movies rated by user \(x\) that are similar to movie \(i\)
- \(w_{ij}\) is the interpolation weight (some real number)
  - We allow: \(\sum_{j \in N(i,x)} w_{ij} \neq 1\)
- \(w_{ij}\) models interaction between pairs of movies (it does not depend on user \(x\))
Idea: Interpolation Weights $w_{ij}$

- $\hat{r}_{xi} = b_{xi} + \sum_{j \in N(i,x)} w_{ij} (r_{xj} - b_{xj})$
- How to set $w_{ij}$?
  - Remember, error metric is: $\frac{1}{|R|} \sqrt{\sum_{(i,x) \in R} (\hat{r}_{xi} - r_{xi})^2}$
  - or equivalently SSE: $\sum_{(i,x) \in R} (\hat{r}_{xi} - r_{xi})^2$
  - Find $w_{ij}$ that minimize SSE on training data!
    - Models relationships between item $i$ and its neighbors $j$
    - $w_{ij}$ can be learned/estimated based on $x$ and all other users that rated $i$

Why is this a good idea?
Goal: Make good recommendations

- Quantify goodness using RMSE:
  Lower RMSE $\Rightarrow$ better recommendations
- Want to make good recommendations on items that user has not yet seen. Can’t really do this!

- Let’s set build a system such that it works well on known (user, item) ratings
  And hope the system will also predict well the unknown ratings
**Recommendations via Optimization**

- **Idea:** Let’s set values $w$ such that they work well on known (user, item) ratings.
- **How to find such values $w$?**
  - **Idea:** Define an objective function and solve the optimization problem.
- Find $w_{ij}$ that minimize $\text{SSE}$ on training data!

$$J(w) = \sum_{x,i} \left( b_{xi} + \sum_{j \in N(i;x)} w_{ij} (r_{xj} - b_{xj}) - r_{xi} \right)^2$$

- Think of $w$ as a vector of numbers.

A simple way to minimize a function $f(x)$:

- Compute the derivative $\nabla f$
- Start at some point $y$ and evaluate $\nabla f(y)$
- Make a step in the reverse direction of the gradient: $y = y - \nabla f(y)$
- Repeat until converged
**Interpolation Weights**

- We have the optimization problem, now what?
- Gradient decent:
  - Iterate until convergence: \( w \leftarrow w - \eta \nabla_w J \)
  - \( \eta \) … learning rate
  - where \( \nabla_w J \) is the gradient (derivative evaluated on data):
    \[
    \nabla_w J = \left[ \frac{\partial J(w)}{\partial w_{ij}} \right] = 2 \sum_x \left( b_{xi} + \sum_{k \in N(i)} w_{ik} (r_{xk} - b_{xk}) \right) - r_{xi} \right) (r_{xj} - b_{xj})
    \]
    for \( j \in \{N(i; x), \forall i, \forall x\} \)
  - \( \frac{\partial J(w)}{\partial w_{ij}} = 0 \) else
- Note: We fix movie \( i \), go over all \( r_{x_i} \) for every movie \( j \) \( \in N(i; x) \), we compute \( \frac{\partial J(w)}{\partial w_{ij}} \)
  - while \( |w_{new} - w_{old}| > \varepsilon \):
    \[
    w_{old} = w_{new}
    w_{new} = w_{old} - \eta \cdot \nabla w_{old}
    \]
So far:  \( \hat{r}_{xi} = b_{xi} + \sum_{j \in N(i;x)} w_{ij} (r_{xj} - b_{xj}) \)

- Weights \( w_{ij} \) derived based on their role; no use of an arbitrary similarity measure \( (w_{ij} \neq s_{ij}) \)
- Explicitly account for interrelationships among the neighboring movies

Next: Latent factor model
- Extract “regional” correlations
Performance of Various Methods

Grand Prize: 0.8563

Netflix: 0.9514

Movie average: 1.0533

User average: 1.0651

Global average: 1.1296

Basic Collaborative filtering: 0.94

CF+Biases+learned weights: 0.91

Grand Prize: 0.8563
**Latent Factor Models**

- "SVD" on Netflix data: \( R \approx Q \cdot P^T \)

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- For now let’s assume we can approximate the rating matrix \( R \) as a product of “thin” \( Q \cdot P^T \)
  - \( R \) has missing entries but let’s ignore that for now!
    - Basically, we will want the reconstruction error to be small on known ratings and we don’t care about the values on the missing ones
How to estimate the missing rating of user $x$ for item $i$?

$$\hat{r}_{xi} = q_i \cdot p_x$$

$$= \sum_f q_{if} \cdot p_{xf}$$

$q_i = \text{row } i \text{ of } Q$

$p_x = \text{column } x \text{ of } P^T$
How to estimate the missing rating of user $x$ for item $i$?

$$\hat{r}_{xi} = q_i \cdot p_x$$

$$= \sum_{f} q_{if} \cdot p_{xf}$$

$q_i$ = row $i$ of $Q$

$p_x$ = column $x$ of $P^T$
Ratings as Products of Factors

- How to estimate the missing rating of user $x$ for item $i$?

\[
\hat{r}_{xi} = q_i \cdot p_x = \sum_{f} q_{if} \cdot p_{xf}
\]

\[
q_i = \text{row } i \text{ of } Q \quad \quad \quad \quad p_x = \text{column } x \text{ of } P^T
\]
Latent Factor Models

Geared towards females

Serious
The Color Purple

Sense and Sensibility

Braveheart

Lethal Weapon

Ocean’s 11

Factor 1

Geared towards males

The Lion King

Factor 2

Independence Day

Factor 2

Funny

Dumb and Dumber

The Princess Diaries

Amadeus

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Recap: SVD

- **Remember SVD:**
  - **A**: Input data matrix
  - **U**: Left singular vecs
  - **V**: Right singular vecs
  - **Σ**: Singular values

- **So in our case:**
  - "SVD" on Netflix data: $R \approx Q \cdot P^T$
  - $A = R$, $Q = U$, $P^T = \Sigma V^T$
  - $\hat{r}_{xi} = q_i \cdot p_x$
SVD: More good stuff

- We already know that SVD gives minimum reconstruction error (Sum of Squared Errors):

\[
\min_{U,V,\Sigma} \sum_{ij \in A} (A_{ij} - [U\Sigma V^T]_{ij})^2
\]

- **Note two things:**
  - **SSE** and **RMSE** are monotonically related:
    - \( RMSE = \frac{1}{c} \sqrt{SSE} \)  
      Great news: SVD is minimizing RMSE
  - **Complication:** The sum in SVD error term is over all entries (no-rating is interpreted as zero-rating). But our \( R \) has missing entries!
Latent Factor Models

- SVD isn’t defined when entries are missing!
- Use specialized methods to find $P, Q$

\[ \min_{P, Q} \sum_{(i,x) \in \mathcal{R}} (r_{xi} - q_i \cdot p_x)^2 \]

\[ \hat{r}_{xi} = q_i \cdot p_x \]

- Note:
  - We don’t require cols of $P, Q$ to be orthogonal/unit length
  - $P, Q$ map users/movies to a latent space
  - The most popular model among Netflix contestants

Finding the Latent Factors
Our goal is to find $P$ and $Q$ such that:

$$\min_{P,Q} \sum_{(i,x) \in R} (r_{xi} - q_i \cdot p_x)^2$$
Want to minimize SSE for unseen test data

**Idea:** Minimize SSE on *training data*

- Want large $k$ (# of factors) to capture all the signals
- But, SSE on *test data* begins to rise for $k > 2$

This is a classical example of **overfitting**:

- With too much freedom (too many free parameters) the model starts fitting noise
  - That is it fits too well the training data and thus **not generalizing** well to unseen test data
To solve overfitting we introduce regularization:

- Allow rich model where there are sufficient data
- Shrink aggressively where data are scarce

\[
\min_{P,Q} \sum_{\text{training}} (r_{xi} - q_i p_x)^2 + \left[ \lambda_1 \sum_x \|p_x\|^2 + \lambda_2 \sum_i \|q_i\|^2 \right]
\]

\( \lambda_1, \lambda_2 \ldots \) user set regularization parameters

**Note:** We do not care about the “raw” value of the objective function, but we care in P,Q that achieve the minimum of the objective
The Effect of Regularization

The Princess Diaries
The Color Purple
Sense and Sensibility

The Lion King
Amadeus
Ocean's 11

Factor 1
Geared towards males

Factor 2
Geared towards females

serious

funny

min \sum_{x \in \text{training}} (r_{xi} - q_i, p_i)^2 + \lambda \left( \sum_s \|p_s\|^2 + \sum_i \|q_i\|^2 \right)

min_{factors} "error" + \lambda "length"
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The Color Purple

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The Princess Diaries

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\[
\min_{P,Q} \sum_{x \in \text{training}} (r_{xi} - q_i p_x)^2 + \lambda \left[ \sum_x \|p_x\|^2 + \sum_i \|q_i\|^2 \right]
\]

\[
\min_{\text{factors}} \text{“error”} + \lambda \text{“length”}
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funny

min \sum_{r_{xi} - q_i p_i}^2 + \lambda \left[ \sum_x \|p_x\|^2 + \sum_i \|q_i\|^2 \right]

min factors “error” + \lambda “length”
Want to find matrices $P$ and $Q$:

$$\min_{P,Q} \sum_{\text{training}} (r_{xi} - q_i p_x)^2 + \left[ \lambda_1 \sum_x \|p_x\|^2 + \lambda_2 \sum_i \|q_i\|^2 \right]$$

Gradient decent:

- Initialize $P$ and $Q$ (using SVD, pretend missing ratings are 0)
- Do gradient descent:
  - $P \leftarrow P - \eta \cdot \nabla P$
  - $Q \leftarrow Q - \eta \cdot \nabla Q$
  - where $\nabla Q$ is gradient/derivative of matrix $Q$:
    $$\nabla Q = [\nabla q_{if}] \text{ and } \nabla q_{if} = \sum_{x,i} -2(r_{xi} - q_i p_x) p_{xf} + 2\lambda_2 q_{if}$$
    - Here $q_{if}$ is entry $f$ of row $q_i$ of matrix $Q$
- Observation: Computing gradients is slow!

How to compute gradient of a matrix?

Compute gradient of every element independently!
Gradient Descent (GD) vs. Stochastic GD

- Observation: \( \nabla Q = [\nabla q_{if}] \) where

\[
\nabla q_{if} = \sum_{x,i} -2(r_{xi} - q_{if} p_{xf}) p_{xf} + 2\lambda q_{if} = \sum_{x,i} \nabla Q(r_{xi})
\]

- Here \( q_{if} \) is entry \( f \) of row \( q_i \) of matrix \( Q \)

- Idea: Instead of evaluating gradient over all ratings evaluate it for each individual rating and make a step

- GD: \( Q \leftarrow Q - \eta \nabla Q = Q - \eta [\sum_{x,i} \nabla Q(r_{xi})] \)

- SGD: \( Q \leftarrow Q - \mu \nabla Q(r_{xi}) \)

- Faster convergence!

- Need more steps but each step is computed much faster
Convergence of **GD** vs. **SGD**

**GD** improves the value of the objective function at every step. **SGD** improves the value but in a “noisy” way. **GD** takes fewer steps to converge but each step takes much longer to compute. In practice, **SGD** is much faster!
Stochastic Gradient Descent

- Stochastic gradient decent:
  - Initialize $P$ and $Q$ (using SVD, pretend missing ratings are 0)
  - Then iterate over the ratings (multiple times if necessary) and update factors:

    For each $r_{xi}$:
    - $\varepsilon_{xi} = 2(r_{xi} - q_i \cdot p_x)$ (derivative of the “error”)
    - $q_i \leftarrow q_i + \mu_1 (\varepsilon_{xi} p_x - \lambda_2 q_i)$ (update equation)
    - $p_x \leftarrow p_x + \mu_2 (\varepsilon_{xi} q_i - \lambda_1 p_x)$ (update equation)

- 2 for loops:
  - For until convergence:
    - For each $r_{xi}$
      - Compute gradient, do a “step”
Extending Latent Factor Model to Include Biases
**Modeling Biases and Interactions**

- **user bias**
- **movie bias**
- **user-movie interaction**

**Baseline predictor**
- Separates users and movies
- Benefits from insights into user’s behavior
- Among the main practical contributions of the competition

**User-Movie interaction**
- Characterizes the matching between users and movies
- Attracts most research in the field
- Benefits from algorithmic and mathematical innovations

- \( \mu \) = overall mean rating
- \( b_x \) = bias of user \( x \)
- \( b_i \) = bias of movie \( i \)
Baseline Predictor

- We have expectations on the rating by user $x$ of movie $i$, even without estimating $x$’s attitude towards movies like $i$

- Rating scale of user $x$
- Values of other ratings user gave recently (day-specific mood, anchoring, multi-user accounts)
- (Recent) popularity of movie $i$
- Selection bias; related to number of ratings user gave on the same day (“frequency”)
Putting It All Together

\[ r_{xi} = \mu + b_x + b_i + q_i \cdot p_x \]

- **Example:**
  - Mean rating: \( \mu = 3.7 \)
  - You are a critical reviewer: your ratings are 1 star lower than the mean: \( b_x = -1 \)
  - Star Wars gets a mean rating of 0.5 higher than average movie: \( b_i = +0.5 \)
  - Predicted rating for you on Star Wars:
    \[ = 3.7 - 1 + 0.5 = 3.2 \]
Fitting the New Model

- **Solve:**
  \[
  \min_{Q,P} \sum_{(x,i) \in R} \left( r_{xi} - (\mu + b_x + b_i + q_i p_x)^2 \right)^2
  \]
  
  goodness of fit

  \[
  + \left( \lambda_1 \sum_i \| q_i \|^2 + \lambda_2 \sum_x \| p_x \|^2 + \lambda_3 \sum_x \| b_x \|^2 + \lambda_4 \sum_i \| b_i \|^2 \right)
  \]

  \( \lambda \) is selected via grid-search on a validation set

- **Stochastic gradient decent to find parameters**
  - **Note:** Both biases \( b_x, b_i \) as well as interactions \( q_i, p_x \) are treated as parameters (we estimate them)
Performance of Various Methods

Performance of Various Methods

Global average: 1.1296
User average: 1.0651
Movie average: 1.0533
Netflix: 0.9514
Basic Collaborative filtering: 0.94
Collaborative filtering++: 0.91
Latent factors: 0.90
Latent factors+Biases: 0.89
Grand Prize: 0.8563

The Netflix Challenge: 2006-09
Temporal Biases Of Users

- **Sudden rise in the average movie rating** (early 2004)
  - Improvements in Netflix
  - GUI improvements
  - Meaning of rating changed

- **Movie age**
  - Users prefer new movies without any reasons
  - Older movies are just inherently better than newer ones

Y. Koren, Collaborative filtering with temporal dynamics, KDD '09
Temporal Biases & Factors

- **Original model:**
  \[ r_{xi} = \mu + b_x + b_i + q_i \cdot p_x \]

- **Add time dependence to biases:**
  \[ r_{xi} = \mu + b_x(t) + b_i(t) + q_i \cdot p_x \]
  - Make parameters \( b_x \) and \( b_i \) to depend on time
  - (1) Parameterize time-dependence by linear trends
  - (2) Each bin corresponds to 10 consecutive weeks
  \[ b_i(t) = b_i + b_i,\text{Bin}(t) \]

- **Add temporal dependence to factors**
  - \( p_x(t) \)... user preference vector on day \( t \)

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Y. Koren, Collaborative filtering with temporal dynamics, KDD ’09
Adding Temporal Effects

![Graph showing the relationship between RMSE and Millions of parameters for different models: CF (no time bias), Basic Latent Factors, CF (time bias), Latent Factors w/ Biases, + Linear time factors, + Per-day user biases, and + CF.]
Performance of Various Methods

- Global average: 1.1296
- User average: 1.0651
- Movie average: 1.0533
- Netflix: 0.9514

Basic Collaborative filtering: 0.94
Collaborative filtering++: 0.91
Latent factors: 0.90
Latent factors+Biases: 0.89
Latent factors+Biases+Time: 0.876

Grand Prize: 0.8563

Still no prize! 😞
Getting desperate.
Try a “kitchen sink” approach!
The big picture
Solution of BellKor's Pragmatic Chaos

All developed CF models
- BRISMF
- MF1
- NSVDD
- SVD-Time
- SVR
- Baseline
- KNN
- KNN+time
- VB
- RBM
- SVD
- BK
- DRBM
- SVD++
- ISVD2
- NG
- MF
- RBF
- GTE
- Integrated
- M.

Latent User and Movie Features

Probe Blending

200 blends

Linear Blend 10.09 % improvement
Standing on June 26th 2009

June 26th submission triggers 30-day “last call”
The Last 30 Days

- **Ensemble team formed**
  - Group of other teams on leaderboard forms a new team
  - Relies on combining their models
  - Quickly also get a qualifying score over 10%

- **BellKor**
  - Continue to get small improvements in their scores
  - Realize that they are in direct competition with **Ensemble**

- **Strategy**
  - Both teams carefully monitoring the leaderboard
  - Only sure way to check for improvement is to submit a set of predictions
    - This alerts the other team of your latest score
Submissions limited to 1 a day
- Only 1 final submission could be made in the last 24h

24 hours before deadline...
- BellKor team member in Austria notices (by chance) that Ensemble posts a score that is slightly better than BellKor’s

Frantic last 24 hours for both teams
- Much computer time on final optimization
- Carefully calibrated to end about an hour before deadline

Final submissions
- BellKor submits a little early (on purpose), 40 mins before deadline
- Ensemble submits their final entry 20 mins later
- ....and everyone waits....
<table>
<thead>
<tr>
<th>Rank</th>
<th>Team Name</th>
<th>Best Test Score</th>
<th>% Improvement</th>
<th>Best Submit Time</th>
</tr>
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<tr>
<td>1</td>
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**Progress Prize 2008** - RMSE = 0.8627 - Winning Team: BellKor in BigChaos

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<th>Team Name</th>
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<th>Best Submit Time</th>
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<td>13</td>
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**Progress Prize 2007** - RMSE = 0.8758 - Winning Team: BellKor in BigChaos

<table>
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<th>Rank</th>
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<th>Best Submit Time</th>
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Million $ Awarded Sept 21st 2009
Acknowledgments

- Some slides and plots borrowed from Yehuda Koren, Robert Bell and Padhraic Smyth
- **Further reading:**
  - Y. Koren, Collaborative filtering with temporal dynamics, KDD ’09
  - [http://www2.research.att.com/~volinsky/netflix/bpc.html](http://www2.research.att.com/~volinsky/netflix/bpc.html)
  - [http://www.the-ensemble.com/](http://www.the-ensemble.com/)