



Machine Learning

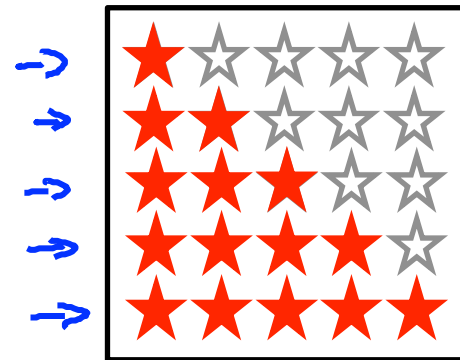
# Recommender Systems

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## Problem formulation

## Example: Predicting movie ratings

→ User rates movies using ~~one~~ to five stars  
 zero



Movie	Alice (1)	Bob (2)	Carol (3)	Dave (4)
Love at last	5	5	0	0
Romance forever	5	?	?	0
Cute puppies of love	?	5	0	?
Nonstop car chases	0	0	5	4
Swords vs. karate	0	0	5	?

$$n_u = 4$$

$$n_m = 5$$

0, ..., 5

→  $n_u$  = no. users

→  $n_m$  = no. movies

→  $r(i, j) = 1$  if user  $j$  has rated movie  $i$

→  $y^{(i, j)}$  = rating given by user  $j$  to movie  $i$  (defined only if  $r(i, j) = 1$ )



Machine Learning

# Recommender Systems

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Content-based  
recommendations

# Content-based recommender systems

$n_u = 4, n_m = 5$

$x_0 = 1$

Movie	Alice (1) $\theta^{(1)}$	Bob (2) $\theta^{(2)}$	Carol (3) $\theta^{(3)}$	Dave (4) $\theta^{(4)}$
Love at last 1	5	5	0	0
Romance forever 2	5	?	?	0
Cute puppies of love 3	?	4	0	?
Nonstop car chases 4	0	0	5	4
Swords vs. karate 5	0	0	5	?

$x^{(i)} \rightarrow$

$x^{(1)} = \begin{bmatrix} 1 \\ 0.9 \\ 0 \end{bmatrix}$

$n=2$

→ For each user  $j$ , learn a parameter  $\theta^{(j)} \in \mathbb{R}^3$ . Predict user  $j$  as rating movie  $i$  with  $x^{(i)}$  stars.  $\theta^{(j)} \in \mathbb{R}^{n+1}$

$$x^{(3)} = \begin{bmatrix} 1 \\ 0.99 \\ 0 \end{bmatrix} \leftrightarrow \theta^{(1)} = \begin{bmatrix} 0 \\ 5 \\ 0 \end{bmatrix}$$

$$(\theta^{(1)})^T x^{(3)} = 5 \times 0.99 = 4.95$$

## Problem formulation

- $r(i, j) = 1$  if user  $j$  has rated movie  $i$  (0 otherwise)
- $y^{(i,j)}$  = rating by user  $j$  on movie  $i$  (if defined)

→  $\theta^{(j)}$  = parameter vector for user  $j$

→  $x^{(i)}$  = feature vector for movie  $i$

→ For user  $j$ , movie  $i$ , predicted rating:  $(\theta^{(j)})^T (x^{(i)})$

$$\theta^{(j)} \in \mathbb{R}^{n+1}$$

→  $m^{(j)}$  = no. of movies rated by user  $j$

To learn  $\theta^{(j)}$ :

$$\min_{\theta^{(j)}} \frac{1}{2} \sum_{i: r(i,j)=1} \left( (\theta^{(j)})^T x^{(i)} - y^{(i,j)} \right)^2 + \frac{\lambda}{2} \sum_{k=1}^n (\theta_k^{(j)})^2$$

## Optimization objective:

To learn  $\theta^{(j)}$  (parameter for user  $j$ ):

$$\rightarrow \min_{\theta^{(j)}} \underbrace{\frac{1}{2} \sum_{i:r(i,j)=1} \left( (\theta^{(j)})^T x^{(i)} - y^{(i,j)} \right)^2}_{\text{user } j \text{ loss}} + \underbrace{\frac{\lambda}{2} \sum_{k=1}^n (\theta_k^{(j)})^2}_{\text{regularization}}$$

To learn  $\theta^{(1)}$ ,  $\theta^{(2)}$ , ...,  $\theta^{(n_u)}$ :

$$\min_{\theta^{(1)}, \dots, \theta^{(n_u)}} \frac{1}{2} \sum_{j=1}^{n_u} \sum_{i:r(i,j)=1} \left( (\theta^{(j)})^T x^{(i)} - y^{(i,j)} \right)^2 + \frac{\lambda}{2} \sum_{j=1}^{n_u} \sum_{k=1}^n (\theta_k^{(j)})^2$$

$\theta^{(1)}, \dots, \theta^{(n_u)}$

## Optimization algorithm:

$$\min_{\theta^{(1)}, \dots, \theta^{(n_u)}} \underbrace{\frac{1}{2} \sum_{j=1}^{n_u} \sum_{i:r(i,j)=1} \left( (\theta^{(j)})^T x^{(i)} - y^{(i,j)} \right)^2 + \frac{\lambda}{2} \sum_{j=1}^{n_u} \sum_{k=1}^n (\theta_k^{(j)})^2}_{J(\theta^{(1)}, \dots, \theta^{(n_u)})}$$

Gradient descent update:

$$\theta_k^{(j)} := \theta_k^{(j)} - \alpha \sum_{i:r(i,j)=1} \left( (\theta^{(j)})^T x^{(i)} - y^{(i,j)} \right) x_k^{(i)} \quad \text{(for } k = 0 \text{)}$$

$$\theta_k^{(j)} := \theta_k^{(j)} - \alpha \left( \sum_{i:r(i,j)=1} \left( (\theta^{(j)})^T x^{(i)} - y^{(i,j)} \right) x_k^{(i)} + \lambda \theta_k^{(j)} \right) \quad \text{(for } k \neq 0 \text{)}$$

$\frac{\partial}{\partial \theta_k^{(j)}} J(\theta^{(1)}, \dots, \theta^{(n_u)})$



Machine Learning



# Recommender Systems

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## Collaborative filtering



# Problem motivation

Movie	Alice (1)	Bob (2)	Carol (3)	Dave (4)	 $x_1$	 $x_2$
					(romance)	(action)
Love at last	5	5	0	0	0.9	0
Romance forever	5	?	?	0	1.0	0.01
Cute puppies of love	?	4	0	?	0.99	0
Nonstop car chases	0	0	5	4	0.1	1.0
Swords vs. karate	0	0	5	?	0	0.9

# Problem motivation

Movie	Alice (1) $\theta^{(1)}$	Bob (2) $\theta^{(2)}$	Carol (3) $\theta^{(3)}$	Dave (4) $\theta^{(4)}$	$x_1$ (romance) $\downarrow$	$x_2$ (action) $\downarrow$
$x^{(1)}$ Love at last	$\rightarrow 5$	$\rightarrow 5$	$\rightarrow 0$	$\rightarrow 0$	$\rightarrow 1.0$	$\rightarrow 0.0$
Romance forever	5	?	?	0	[?]	[?]
Cute puppies of love	?	4	0	?	[?]	[?]
Nonstop car chases	0	0	5	4	[?]	[?]
Swords vs. karate	0	0	5	?	[?]	[?]

$x^{(1)} = \begin{bmatrix} 1.0 \\ 0.0 \end{bmatrix}$   
 $\theta^{(j)}$   
 $\theta^{(1)} = \begin{bmatrix} 0 \\ 5 \\ 0 \end{bmatrix}$ ,  $\theta^{(2)} = \begin{bmatrix} 0 \\ 5 \\ 0 \end{bmatrix}$ ,  $\theta^{(3)} = \begin{bmatrix} 0 \\ 0 \\ 5 \end{bmatrix}$ ,  $\theta^{(4)} = \begin{bmatrix} 0 \\ 0 \\ 5 \end{bmatrix}$   
 $(\theta^{(1)})^T x^{(1)} \approx 5$   
 $(\theta^{(2)})^T x^{(1)} \approx 5$   
 $(\theta^{(3)})^T x^{(1)} \approx 0$   
 $(\theta^{(4)})^T x^{(1)} \approx 0$

# Optimization algorithm

Given  $\theta^{(1)}, \dots, \theta^{(n_u)}$ , to learn  $x^{(i)}$ :

$$\min_{x^{(i)}} \frac{1}{2} \sum_{j:r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)})^2 + \frac{\lambda}{2} \sum_{k=1}^n (x_k^{(i)})^2$$

Given  $\theta^{(1)}, \dots, \theta^{(n_u)}$ , to learn  $x^{(1)}, \dots, x^{(n_m)}$ :

$$\min_{x^{(1)}, \dots, x^{(n_m)}} \frac{1}{2} \sum_{i=1}^{n_m} \sum_{j:r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)})^2 + \frac{\lambda}{2} \sum_{i=1}^{n_m} \sum_{k=1}^n (x_k^{(i)})^2$$

# Collaborative filtering

Given  $x^{(1)}, \dots, x^{(n_m)}$  (and movie ratings),  
can estimate  $\theta^{(1)}, \dots, \theta^{(n_u)}$  ↗

$\sigma^{(i,j)}$   
 $y^{(i,j)}$

Given  $\theta^{(1)}, \dots, \theta^{(n_u)}$ ,  
can estimate  $x^{(1)}, \dots, x^{(n_m)}$

Guess  $\Theta \rightarrow x \rightarrow \Theta \rightarrow x \rightarrow \Theta \rightarrow x \rightarrow \dots$



Machine Learning

# Recommender Systems

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Collaborative  
filtering algorithm

# Collaborative filtering optimization objective

→ Given  $x^{(1)}, \dots, x^{(n_m)}$ , estimate  $\theta^{(1)}, \dots, \theta^{(n_u)}$ :

$$\min_{\theta^{(1)}, \dots, \theta^{(n_u)}} \left[ \frac{1}{2} \sum_{j=1}^{n_u} \sum_{i:r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)})^2 + \frac{\lambda}{2} \sum_{j=1}^{n_u} \sum_{k=1}^n (\theta_k^{(j)})^2 \right]$$

$(i,j) : r(i,j)=1$   
 $x \in \mathbb{R}^n$   
 $\theta \in \mathbb{R}^n$   
 $x_i = 1$

→ Given  $\theta^{(1)}, \dots, \theta^{(n_u)}$ , estimate  $x^{(1)}, \dots, x^{(n_m)}$ :

$$\min_{x^{(1)}, \dots, x^{(n_m)}} \left[ \frac{1}{2} \sum_{i=1}^{n_m} \sum_{j:r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)})^2 + \frac{\lambda}{2} \sum_{i=1}^{n_m} \sum_{k=1}^n (x_k^{(i)})^2 \right]$$

Minimizing  $x^{(1)}, \dots, x^{(n_m)}$  and  $\theta^{(1)}, \dots, \theta^{(n_u)}$  simultaneously:

$$J(x^{(1)}, \dots, x^{(n_m)}, \theta^{(1)}, \dots, \theta^{(n_u)}) = \frac{1}{2} \sum_{(i,j):r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)})^2 + \frac{\lambda}{2} \sum_{i=1}^{n_m} \sum_{k=1}^n (x_k^{(i)})^2 + \frac{\lambda}{2} \sum_{j=1}^{n_u} \sum_{k=1}^n (\theta_k^{(j)})^2$$

→  $\min_{\substack{x^{(1)}, \dots, x^{(n_m)} \\ \theta^{(1)}, \dots, \theta^{(n_u)}}} J(x^{(1)}, \dots, x^{(n_m)}, \theta^{(1)}, \dots, \theta^{(n_u)})$

$\theta \rightarrow x \rightarrow \theta \rightarrow x \rightarrow \dots$

# Collaborative filtering algorithm

- 1. Initialize  $x^{(1)}, \dots, x^{(n_m)}, \theta^{(1)}, \dots, \theta^{(n_u)}$  to small random values.
- 2. Minimize  $J(x^{(1)}, \dots, x^{(n_m)}, \theta^{(1)}, \dots, \theta^{(n_u)})$  using gradient descent (or an advanced optimization algorithm). E.g. for every  $j = 1, \dots, n_u, i = 1, \dots, n_m$  :

$$x_k^{(i)} := x_k^{(i)} - \alpha \left( \sum_{j:r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)}) \theta_k^{(j)} + \lambda x_k^{(i)} \right)$$

$$\theta_k^{(j)} := \theta_k^{(j)} - \alpha \left( \sum_{i:r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)}) x_k^{(i)} + \lambda \theta_k^{(j)} \right)$$

- 3. For a user with parameters  $\theta$  and a movie with (learned) features  $x$ , predict a star rating of  $\theta^T x$ .

$$(\theta^{(j)})^T (x^{(i)})$$

~~$x_0 = 1$~~

$x \in \mathbb{R}^n, \theta \in \mathbb{R}^n$

~~$\theta_0$~~   
 $\theta_1$   
 $\dots$   
 $\theta_n$

$\frac{\partial}{\partial x_k^{(i)}} J(\dots)$



Machine Learning

# Recommender Systems

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Vectorization:  
Low rank matrix  
factorization



# Collaborative filtering

Movie	Alice (1)	Bob (2)	Carol (3)	Dave (4)
Love at last	5	5	0	0
Romance forever	5	?	?	0
Cute puppies of love	?	4	0	?
Nonstop car chases	0	0	5	4
Swords vs. karate	0	0	5	?

↑ ↑ ↑ ↑

$$n_m = 5$$
$$n_u = 4$$

$$Y = \begin{bmatrix} 5 & 5 & 0 & 0 \\ 5 & ? & ? & 0 \\ ? & 4 & 0 & ? \\ 0 & 0 & 5 & 4 \\ 0 & 0 & 5 & 0 \end{bmatrix}$$

$y^{(i,j)}$

# Collaborative filtering

$$Y = \begin{bmatrix} 5 & 5 & 0 & 0 \\ 5 & ? & ? & 0 \\ ? & 4 & 0 & ? \\ 0 & 0 & 5 & 4 \\ 0 & 0 & 5 & 0 \end{bmatrix}$$

Predicted ratings:

$$\begin{bmatrix} (\theta^{(1)})^T(x^{(1)}) & (\theta^{(2)})^T(x^{(1)}) & \dots & (\theta^{(n_u)})^T(x^{(1)}) \\ (\theta^{(1)})^T(x^{(2)}) & (\theta^{(2)})^T(x^{(2)}) & \dots & (\theta^{(n_u)})^T(x^{(2)}) \\ \vdots & \vdots & \vdots & \vdots \\ (\theta^{(1)})^T(x^{(n_m)}) & (\theta^{(2)})^T(x^{(n_m)}) & \dots & (\theta^{(n_u)})^T(x^{(n_m)}) \end{bmatrix}$$

$$X = \begin{bmatrix} -(x^{(1)})^T \\ -(x^{(2)})^T \\ \vdots \\ -(x^{(n_m)})^T \end{bmatrix}$$

$$\Theta = \begin{bmatrix} -(\theta^{(1)})^T \\ -(\theta^{(2)})^T \\ \vdots \\ -(\theta^{(n_u)})^T \end{bmatrix}$$

→ Low rank matrix factorization

## Finding related movies

For each product  $i$ , we learn a feature vector  $\underline{x^{(i)}} \in \mathbb{R}^n$ .

→  $x_1 = \text{romance}$ ,  $x_2 = \text{action}$ ,  $x_3 = \text{comedy}$ ,  $x_4 = \dots$

How to find movies  $j$  related to movie  $i$ ?

Small  $\|x^{(i)} - x^{(j)}\| \rightarrow$  movie  $j$  and  $i$  are "similar"

5 most similar movies to movie  $i$ :

Find the 5 movies  $j$  with the smallest  $\|x^{(i)} - x^{(j)}\|$ .



Machine Learning

# Recommender Systems

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Implementational  
detail: Mean  
normalization

# Users who have not rated any movies

Movie	Alice (1)	Bob (2)	Carol (3)	Dave (4)	Eve (5)
→ Love at last	<u>5</u>	<u>5</u>	0	0	<u>?</u>
Romance forever	5	?	?	0	<u>?</u>
Cute puppies of love	?	4	0	?	<u>?</u>
Nonstop car chases	0	0	5	4	<u>?</u>
→ Swords vs. karate	0	0	<u>5</u>	?	<u>?</u>

$$Y = \begin{bmatrix} 5 & 5 & 0 & 0 & ? \\ 5 & ? & ? & 0 & ? \\ ? & 4 & 0 & ? & ? \\ 0 & 0 & 5 & 4 & ? \\ 0 & 0 & 5 & 0 & ? \end{bmatrix}$$

$$\min_{\substack{x^{(1)}, \dots, x^{(n_m)} \\ \theta^{(1)}, \dots, \theta^{(n_u)}}} \frac{1}{2} \sum_{(i,j): r(i,j)=1} ((\theta^{(j)})^T x^{(i)} - y^{(i,j)})^2 + \frac{\lambda}{2} \sum_{i=1}^{n_m} \sum_{k=1}^n (x_k^{(i)})^2 + \frac{\lambda}{2} \sum_{j=1}^{n_u} \sum_{k=1}^n (\theta_k^{(j)})^2$$

$$n=2$$

$$\underline{\theta}^{(5)} \in \mathbb{R}^2$$

$$\underline{\theta}^{(5)} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$(\underline{\theta}^{(5)})^T \underline{x}^{(i)} = 0$$

$$\frac{\lambda}{2} [(\theta_1^{(5)})^2 + (\theta_2^{(5)})^2] \leftarrow$$

## Mean Normalization:

$$Y = \begin{bmatrix} 5 & 5 & 0 & 0 & ? \\ 5 & ? & ? & 0 & ? \\ ? & 4 & 0 & ? & ? \\ 0 & 0 & 5 & 4 & ? \\ 0 & 0 & 5 & 0 & ? \end{bmatrix}$$

Handwritten annotations: Blue circles around the first row's first four elements (5, 5, 0, 0) and the last element (?). Blue arrows point from the first four elements to the right, with values 2.5, 2.5, 2, and 1.25 written next to them. A blue box highlights the last column's first four elements (2.5, 2.5, 2, 1.25).

$$\mu = \begin{bmatrix} 2.5 \\ 2.5 \\ 2 \\ 2.25 \\ 1.25 \end{bmatrix}$$

Handwritten annotations: Blue circles around the first and last elements (2.5 and 1.25). Blue arrows point from the first and last elements to the right.

$\rightarrow \underline{Y} =$

$$\begin{bmatrix} 2.5 & 2.5 & -2.5 & -2.5 & ? \\ 2.5 & ? & ? & -2.5 & ? \\ ? & 2 & -2 & ? & ? \\ -2.25 & -2.25 & 2.75 & 1.75 & ? \\ -1.25 & -1.25 & 3.75 & -1.25 & ? \end{bmatrix}$$

Handwritten annotations: Blue circles around the first row's first four elements (2.5, 2.5, -2.5, -2.5) and the last element (?). Blue arrows point from the first four elements to the right, with values 2.5, 2.5, -2, and 1.75 written next to them. A blue box highlights the last column's first four elements (2.5, 2.5, -2, 1.75).

For user  $j$ , on movie  $i$  predict:

$$\rightarrow (\Theta^{(j)})^T (x^{(i)}) + \mu_i$$

$\downarrow$   
learn  $\underline{\Theta^{(j)}}$ ,  $\underline{x^{(i)}}$

User 5 (Eve):

$$\underline{\Theta^{(5)}} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$$\underbrace{(\Theta^{(5)})^T (x^{(i)})}_{= 0} + \boxed{\mu_i}$$