

Theory

This chapter will introduce some basic theory needed to develop our approach to user modeling. We will first describe our stated enemy, the information overload problem, before delving into how user modeling and, more specifically, recommender systems, is currently used to solve this problem.

This chapter will also introduce the notion of personalized search, a field where our user modeling method will be especially applicable. The next chapter will use these theories to build an *even more personalized approach* to user modeling.

1.1 Information Overload

Information overload conveys the act of receiving *too much information*. The problem is apparent in situations where decisional accuracy turns from improving with more information, to being hindered by too much irrelevant data (Bjorkoy, 2010, p13). Needless to say, this is a widespread phenomenon, with as many definitions as there are fields experiencing the problem. Examples include *sensory overload*, *cognitive overload* and *information anxiety* (Eppler and Mengis, 2004).

Two common tasks quickly become difficult in this situation: Consuming content that is known by the user to be relevant can be drowned out by irrelevant noise. Orthogonally, discovering new, interesting yet unknown content also becomes difficult because of the sheer amount of available content. Finding contemporary examples is not difficult:

- Missing important news articles that get drowned out by irrelevant content.
- Forgetting to reply to an email as new messages keep arriving.
- Discovering sub-par movies because those most relevant are never discovered.

The overload is often likened to a *paradox of choice*, as there may be no problem acquiring the relevant information, but rather identifying this information once acquired. As put by Edmunds and Morris (2000): "The paradox — a surfeit of information and a paucity of useful information." While normal cases of such overload typically result in feelings of being overwhelmed and out of control, Bawden and Robinson (2009) points to studies linking extreme cases to various psychological conditions related to stressful situations, lost attention span, increased distractibility and general impatience.

Kirsh (2000) argues that "the psychological effort of making hard decisions about *pushed* information is the first cause of cognitive overload." According to Kirsh, there will never be a fully satisfiable solution to the problem of overabundant information, but that optimal environments can be designed to increase productivity and reduce the level of stress through careful consideration of the user's needs. In other words, to solve the problems of information overload and content discovery, applications must be able to individually adapt to each user.

An insightful perspective on information overload comes from the study of attention economy. In this context human attention is seen a scarce commodity, offset by how much irrelevant noise is present at any given time. Attention can then be defined as "... focused mental engagement on a particular item of information. Items come into our awareness, we attend to a particular item, and then we decide whether to act" (Davenport and Beck, 2001). To evade information overload is then to maximize available attention, allowing more focus on the most important items of an interface.

Conceptual models used in interaction design can help us see when and where information overload interferes with the user experience. Norman (1988) advocates a model called the seven stages of action, describing how each user goes through several states while using a system (see Figure 1.1, adapted from Norman). First, the user forms a goal and an intention to act. The user then performs a sequence of actions on the world (the interface) meant to align the perceived world and the goals. After performing a set of actions, the new world state is evaluated and perceived. At last, the user evaluates the perception and interpretation of the world in accordance with the original goal.

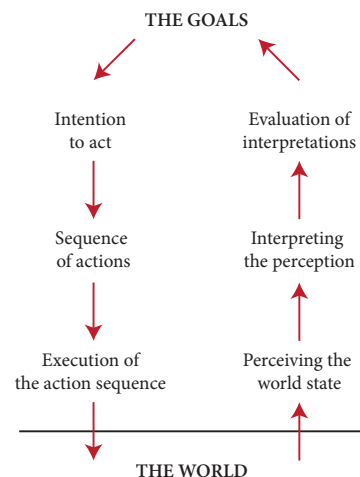


Figure 1.1

As apparent from this model, information overload can interfere both before and after any action is taken. For example, if the application presents too much content, or presents content in a confusing manner, it can be difficult for the user to identify which actions that would help achieve the current goal. Likewise, after actions are taken, the new world state can suffer the same shortcomings of overwhelming scope or lack of presentations, leading to information overload. This precludes the user from properly evaluating the resulting application state.

In short, an application interface can fail both before and after a user tries to interact with it. Information overload happens throughout the interaction process, which is important to know when considering possible solutions.

Online Overload

The Web is a common source of information overload. As we will use the web as an example throughout this paper, this section describes why the Web is so conducive to information overload.

Online information overload is especially pervasive when considering *content aggregating websites*, i.e. sites that collate information from multiple other sites and sources. Online information retrieval (i.e. search engines), fall into this category, as does online newspapers, feed readers and portal websites. As mentioned, the wealth and scope of data are natural culprits of online overload, as well as the varying qualities of websites publishing the information. However, lessons from graph theory can also help us see why information overload occurs on the Web.

Graph theory presents applicable models of the Web that characterize how people navigate between websites, and show how content aggregators form important hubs in the network. These models also show a theoretical foundation for why information overload occurs. In the Web graph, nodes correspond to websites and directed edges between nodes are links from one page to another. The *degree* of a node is defined as its number of edges.

The Internet has the properties of a *small-world network* (Newman and Moore, 2000), a type of random graph, where most nodes are not neighbors, but most nodes are reachable through a small number of edges (See Figure 1.2). This is because of important random shortcuts differentiating the graph from a regular lattice. The graph is not random, but neither is it completely regular. As described by Barabási (2003, p37), the average number of outbound links from a webpage is around 7. From the first page, we can reach 7 other pages. From the second, 49 documents can be reached. After 19 links have been traversed, about 10^{16} pages can be reached (which is more than the actual number of existing web pages, since loops will form in the graph).

The high degree of the Web graph would suggest that finding an optimal path to your desired page is quite difficult. Yet, while it is true that finding the *optimal path* is hard, finding a *good path* is not that big a challenge. When people browse the Web, links are not followed blindly — we use numerous different heuristics to evaluate each link, often

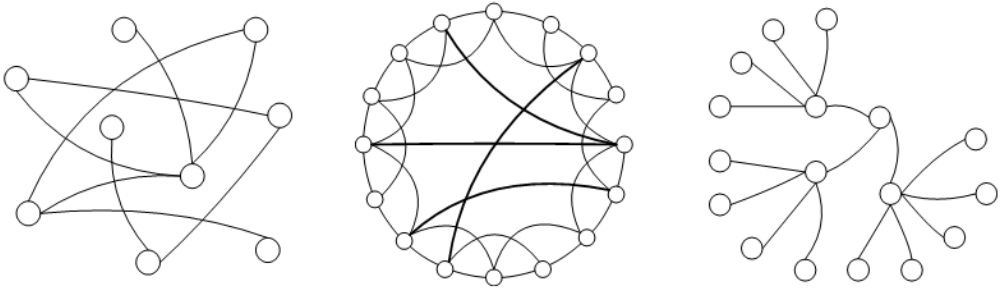


Figure 1.2: Complex Networks, from the left: A random network, a small-world network and a scale-free network (which is a type of small-world network). Figure adapted from [Huang et al. \(2005\)](#).

resulting in a quite good path to where we want to go. So why is the Web still quite challenging to navigate?

As discovered by [Albert et al. \(1999\)](#), the Web also exhibits properties of a *Scale-Free Network* (SFN). They found that in some natural observed networks, there exists a small number of nodes with an extremely high degree. This is also true on the Web — some websites have a huge number of outbound links. For comparison, while a random network is similar to a national highway system, with a regular number of links between major cities, scale-free networks are more like an air traffic system, with central hubs connecting many less active airports ([Barabási, 2003](#), p71).

These highly connected nodes, called *hubs*, are not found in small-world networks or random graphs. As demonstrated by the presence of hubs, the degree distribution of a scale-free network follows a power law, $P(k) \sim k^{-\gamma}$, where $P(k)$ is the probability of a node having k connections and γ is a constant dependent on the type of network, typically in the range $2 < \gamma < 3$. Since the Web has directed edges, we have two power laws: $P_{in}(k) \sim k^{-\gamma_{in}}$ and $P_{out}(k) \sim k^{-\gamma_{out}}$.

[Albert et al. \(1999\)](#) describes a number of studies placing the γ values for the Web in the $[2, 3]$ range, with γ_{out} being slightly higher than γ_{in} . Both these probabilities exhibit power tails (or long tails). In other words, a few important nodes have a huge number of inbound and outbound links — the hubs. [Barabási \(2003, p86\)](#) proposed that hubs emerge in a scale-free networks because of two factors: (1) Growth: Nodes are added to the network one by one, for example when new websites are added to the Internet. (2) Preferential attachment: When new nodes are created, they connect to existing nodes. The probability that the new node will connect to an existing node is proportional to the number of links the existing node has. In other words, older, more established and

central nodes are preferred neighbors.

This is called the Barabási-Albert model (Albert et al., 1999), and the probability for a new node connecting to an existing node is given by $\frac{k_i}{\sum_j k_j}$ in Equation 1.1, where k_i is the number of links pointing to node i .

$$\frac{k_i}{\sum_j k_j} \quad (1.1)$$

Another important topological observation of the Web is how fragmented it is. Barabási (2003, p166) describes the Internet as a number of continents:

The first continent is the *central core*, where most important hubs reside. On this continent, most sites are easily reachable through each other. The second is the *in-continent*, and is defined by the group of websites that often link to sites in the central core, but seldom receive reciprocal links from central hubs. The third is the *out-continent*, which are comprised of sites that are often linked to from the central hub, but seldom link back. Finally, the Internet has many *islands*, or dark nets, which are not accessible through links from other continents. The islands of the Web is why search engines allows web masters to manually add their sites to the search engine index — not all sites are discoverable by following simple links. Some of the Web is topographically close, but a lot of it is not.

Returning to our main topic, the *hubs* often represent the previously mentioned *content aggregating websites*. Search engines, social link aggregators, news portals, et cetera are all hubs of the Internet, emerging from the preferential link attachment of newly created nodes. Factor in the existence of multiple sub-graphs, or continents, and we can intuitively see that navigating the Web is not as easy as it might appear from simple models.

What does seem clear is that these content aggregating hubs are prime candidates for overwhelming their users with information. The fundamental observed structure of the Web creates the need for information brokers that link the net together, and the need for techniques to display a lot of data.

So far we have established that information overload is a pervasive problem, especially on the web. The question now becomes how to best solve this issue. This is where user modeling comes in.

1.2 User Modeling

The term *user modeling* (UM) lacks a strict definition. Broadly speaking, when an application is adapted in some way based on what the system knows about its users, we have user modeling. From predictive modeling methods in machine learning and how to implement these methods, to how interface design is influenced by personalization — the field covers a lot of ground.

It is important to differentiate between adapting the interface of an application and the content of an application. Many user modeling methods strive to personalize the interface itself, e.g. menus, buttons and layout of interface control elements (Jameson, 2009; Fischer, 2001). Adapting the application content, on the other hand, means changing how and what content is displayed. For instance, interface adaption might mean changing the order of items in a menu, while content adaption might mean changing the order and emphasis of results in a web search interface.

We are interested in adapting the content of an application since the source of our overload problem often comes down to a mismatch between presented content and desired content. Examples of such user modeling include:

- Translating content based on a user's geographical location.
- Suggesting interesting items based on previous activity.
- Reorganizing or filtering content based on predicted user relevance.
- Changing the presentation of content to match personal preferences or abilities.

The fields of Artificial Intelligence (AI) and Human-Computer Interaction (HCI) share a common goal solving information overload through user modeling. However, as described by Lieberman (2009), they have different approaches and their efforts are seldom combined: while AI researchers often view contributions from HCI as trivial cosmetics, the HCI camp tends to view AI as unreliable and unpredictable — surefire aspects of poor interaction design. Luckily, according to Kobsa (2001), recent research has blurred the lines between the AI and HCI in user modeling.

In AI, user modeling refers to precise algorithms and methods that infer knowledge about a user based on past interaction (e.g. Pazzani and Billsus (2007); Smyth (2007); Alshamri and Bharadwaj (2008); Resnick et al. (1994)). By examining previous actions, predictions can be made of how the user will react to future information. This new knowledge is then embedded in a model of the user, which can predict future actions and reactions. For instance, an individual user model may predict how interesting an

unseen article will be to a user, based on previous feedback on similar articles or the feedback of similar users.

HCI aims to meet user demands for interaction. User modeling plays a crucial role in this task. Unlike the formal user modeling methods of AI, user models in HCI are often cognitive approximations, manually developed by researchers to describe different types of users (e.g. Fischer (2001); Jameson (2009); Cato (2001)). These models are then utilized by interaction designers to properly design the computer interface based on a models predictions of its user's preferences. Totterdell and Rautenbach (1990) describes user modeling in interaction design as a collection of deferred parameters: "The designer defers some of the design parameters such that they can be selected or fixed by features of the environment at the time of interaction [...] Conventional systems are special cases of adaptive systems in which the parameters have been pre-set."

This paper is concerned with the AI approach to user modeling, and in particular, the use of *recommender systems* (RS). As our goal is to combine different RSs into one coherent user model, we will now describe what an RS entails, and introduce some of the many algorithms they employ.

1.3 Recommender Systems

The name might seem constraining, but recommender systems are incredibly powerful methods in user modeling. Whenever we wish to predict the relevance of an item to a user, recommender systems are the tools to use. Such systems are commonly used on the web to provide a host of predictive functionality, including:

- Recommending products like books or movies based on past purchases.
- Suggesting new social connections based on an existing social graph.
- Recommending items based the activity of similar or like-minded users.
- Ordering news articles by predicted individual relevance.
- Personalizing search results based on the current user.

Common to these examples are a set of users, a set of items, and a sparse set of explicit ratings or preferences. Items can be anything: Documents, movies, music, places, people, or indeed other users. A recommender system is best described by graph and graph operations, even though the underlying algorithms might not use this as the representation. Mirza and Keller (2003) explains how any RS can be expressed as a graph

traversal algorithm. Items and users are nodes, while ratings, social connections et cetera are edges between the nodes. An RS performs predictive reasoning on this graph by estimating the strenghts of hypothetical connections between nodes that are not explicitly connected.

For example, if a user has rated some of the movies in a movie recommendation system, we use these ratings to predict how well the user will like unseen movies, based on a movies ratings from users similar to the one in question. In social networks, recommender systems can be used to infer new social relations based on existing connections. The principle is the same: By evaluating current explicit connections, and the connections of similar users, new connections can be predicted. Recommender systems are then powerful methods for user modeling, personalization and fighting information overload, because of their ability to infer how relevant and item (or another user) will be to the current user.

Formally, a recommender system can be seen as a quintuple, $RS = (I, U, R, F, M)$, where I is the set of items (e.g. products, articles or movies) and U is the set of users. R is the set of known connections, for example explicit preferences given by users for certain items, or connections in a social graph. F is a framework for representing the items, users and ratings, for example a graph or matrix. M is the actual user modeling method used to infer unknown ratings for predicting a user's preference for an unrated item. This is where AI comes in.

In [Adomavicius and Tuzhilin \(2005\)](#), M is seen as a utility function $f : U \times I \rightarrow S$. Here, f is a function that maps the set of users and items into a fully ordered set of items S , ranked by their utility (i.e. rating) to each user. In other words, S is the completely specified version of R , where each user has either an explicit, implicit or predicted preference for each item in I . To predict the best unrated item for each user, we simply find the item with the highest expected utility:

$$\forall u \in U, i'_u = \arg \max_{i \in I} f(u, i)$$

The utility function u depends on the modeling method being used, the active user and the item in question. The *reason* for using a recommender system is that the utility u is not defined for the entire $U \times I$ space, i.e. the system does not explicitly know the utility of each item for each user. The point of a recommender system is then to extrapolate u to cover the entire user-item space. In other words, to be able to rank items according to user preferences, the system must be able to predict each user's reaction to items they have not yet explicitly rated themselves. This is where predictive user models come in

handy.

Another popular way of describing, and implementing an RS is using a simple matrix. Here, one dimension represents users, the other dimension represents items, and each cell corresponds to an explicit rating. This matrix then becomes the framework F in our RS quintuple:

$$R_{u,i} = \begin{pmatrix} r_{1,1} & r_{1,2} & \cdots & r_{1,i} \\ r_{2,1} & r_{2,2} & \cdots & r_{2,i} \\ \vdots & \vdots & \ddots & \vdots \\ r_{u,1} & r_{u,2} & \cdots & r_{u,i} \end{pmatrix}$$

Critically, these matrices are usually extremely sparse (i.e. most of the cells are empty). Consider that while there may be a large number of users and items, each individual user only rates or connects to a few number of items. For example, in the seminal Netflix Challenge movie recommender dataset, almost 99% of the potential user/item pairs have no rating (Bell and Koren, 2007a, p1). In other words, the recommender system must be able to produce results from a matrix where only 1% of the cells have meaningful values.

Naturally, this is the defining characteristic of many recommender systems: the ability to extract meaningful patterns from sparse data, through dimensionality reduction, neighborhood estimation and other methods, as we shall see.

Recommender systems face many challenges other than the sparsity problem. A directly related problem is the need for large datasets. Since the data is often sparse, the systems will most often perform well if used on large numbers of items and users. As in many machine learning methods, concept drift, where the characteristics of a user or item changes over time, is also always present.

The performance of RSs is often closely tied to their computational complexity. Real world usage of the most precise methods is often hindered by the computational power needed to actually put them into production.

Finally, the scale of the data in question should be a concern. If the ratings are ordinal data (e.g. 1-5) input directly by users, the RS should take into account the domain specific meaning of these intervals. For example, in a system for rating movies, the jump between ratings 4-5 might not have the same significance as the jump from 2-3. However, this is a fact seldom mentioned in the literature. Most RSs employ metrics that assume a normal distribution, and even the common evaluation techniques such as RMSE or MAE treat

ordinal data as a continuous scale.

Prediction

The crucial part of any RS is how it predicts unknown ratings. (Note that although we use "ratings", "utility", "preference", "relevance" and "connection strength" depending on the context, they all basically mean the same.) Because of this, each method is best categorized based on a few dimensions of its predictive capabilities (see Table 1.1). In our taxonomy, these dimensions are: *data*, *method*, *granularity*, *temporality* and *agents*.

The *data* variable represents what data the RS uses to perform predictions. Content-based methods use only the items, inter-item relations, and an individual user's past history as predictive of future actions (Pazzani and Billsus, 2007). By only considering the individual user in adapting an application, highly personal models can be created. However, such methods often require a lot of interaction before reliable models can be created (Adomavicius and Tuzhilin, 2005). The problem of having to do complex inference from little data, as is often is in content-based predictions, is often called the *sparsity problem* or the *cold start* problem. This is closely related to the problem of *overfitting* data, where the algorithms creates models that match the training data, but not the actual underlying relationships. A lot of research looks at ways to overcome sparse data, i.e. achieving "warmer" cold start. When using content-based predictions, the utility function $f(u, i)$ of user u and item i is extrapolated from $f(u, i_u)$, where i is an item similar to i_u and $f(u, i_u)$ is known.

Collaborative or social recommendations build predictive models for users based on the actions of similar users (Schafer et al., 2007). The observation is that similar users should have similar usage and action patterns. By using data from more than one user, expansive models may be built. These methods are especially useful when considering new users of a service. A central problem with collaborative methods is that the resulting

Variable	Values
Data	Content-based Collaborative Hybrid
Method	Heuristic Model-based
Granularity	Canonical Typical Individual
Temporality	Short-term Long-term
Agents	Implicit Explicit

Table 1.1: A taxonomy of recommender systems. From Bjorkoy (2010).

model is not as individually tailored as one created through content-based prediction. Collaborative models must be careful not to represent the *average* user, but a single individual. When using a collaborative method, the utility $f(u, i)$ of item i for user u is extrapolated from $f(u_j, i)$ where u_j is a user similar to u .

Because of the *new user problem* of content-based prediction and the *average user problem* of collaborative prediction, many systems use a hybrid approach (Burke, 2007). By combining content-based and collaborative methods, systems that properly handle predictions for new users and avoid too much generalization in the models can be achieved.

The *method* variable, is another way to classify recommenders. Orthogonal to what data the method uses, this variable concerns *how* the data is used to produce recommendations. First we have the *model-based* approach, where the recommender system builds predictive models based on the known data. Unseen items can then be fed into this model to compute its estimated utility score. For example, creating a Bayesian networks from past interaction is a model-based approach. The other category is the *heuristic* or *memory-based* approach. These methods use the raw data of items, users and ratings to directly estimate unknown utility values. For example, recommending items similar to the ones already rated by computing the cosine similarity of their feature vectors is a heuristic approach.

The *granularity* variable tells whether this approach creates models for the canonical user, stereotypical users or individual users. Rich (1979) presented one of the first user modeling systems based on stereotypes, used to predict which books in a library each user would most enjoy. Here, a dialogue between the system and the user was performed to place the user into a set of stereotypes. Each stereotype has a set of *facets* which is then used to match books and users.

Temporality refers to how volatile the gathered knowledge will be. While most RSs produce long term, relatively stable knowledge based on lasting user preference and taste, some systems use fluctuating parameters such as the time of day, exact location and the current context to produce recommendations. For example, Horvitz et al. (2003) used clues from a user's calendar, camera and other sensors to determine the attentional state of the user before delivering personalized and contextual notifications.

The *agents* variable signifies whether the knowledge gathering and presentation is implicit and opaque, or explicit and requires dedicated user interaction. Explicit feedback through ratings is common in movie, product or music rating services (e.g. Bell et al. (2007b); Basu et al. (1998); Hotho et al. (2006)). However, for other services such as personalized search, implicit mining of query logs and user interaction is often used to

build user models (e.g. Shen et al. (2005); Agichtein et al. (2006); Speretta and Gauch (2000); Teevan et al. (2005))

Approaches

Because our solution will combine different recommender systems, we need a short introduction to some of the approaches we will combine. Let us take a closer look at (1) *baseline ratings*, (2) *neighborhood estimation*, (3) *dimensionality reduction*, and (4) *network traversal*. This is by no means an exhaustive list, but rather a quick rundown of common approaches in recommender systems, that we will use in the next chapter. See Adomavicius and Tuzhilin (2005), Pazzani and Billsus (2007), Schafer et al. (2007) or Bjorkoy (2010) for a more comprehensive exploration of different types of recommenders.

(1) *Baseline ratings* are the simplest family of recommender systems, based on item and user rating averages. The data is content-based, and used to compute heuristic predictions. This is done on a per-user, individual basis and collects long term knowledge so far as the user is rational in most of his or her ratings. While simple in nature, they are often helpful as starting points for more complex systems, or as benchmarks for exploring new approaches. (Koren, 2008, p2) computes the baselines for items and users, and use more involved methods to move this starting point in some direction. The baseline for a user/item pair is given by

$$b_{ui} = \mu + b_u + b_i$$

where μ is the average system rating, b_u is the user baseline and b_i is the item baseline. The user and item baselines correspond to how the user's and item's ratings deviate from the norm. This makes sense as some items may be consistently rated higher than the average, some users may be highly critical in their assessments, and so on. Koren computes these baselines by solving the least squares problem

$$\min_{b^*} = \sum_{(u,i) \in R} (r_{ui} - \mu - b_u - b_i)^2 + \lambda (\sum_u b_u^2 + \sum_i b_i^2)$$

which finds baselines that fit the given ratings while trying to reduce overfitting (by punishing greater values, as weighted by the λ parameter). By using baselines instead of simple averages, more complex predictors gain a better starting point, or in other words, a better average.

Another approach based on simple averages is the *Slope One* family of collaborative filtering algorithms. As introduced by [Lemire and Maclachlan \(2005\)](#), these algorithms predict unknown ratings based on the average difference in ratings between two items. For example, if item i is on average rated δ points above item j , and the user u has rated item j , that is, we know r_{uj} , the predicted rating of i is simply $r_{uj} + \delta$, for all ratings that match this pattern. In other words,

$$\hat{r}_{ui} = \frac{\sum_{j \in K_u} \text{ratings}(j) \times (r_{uj} + \text{diff}(i, j))}{\sum_{j \in K_u} \text{ratings}(j)},$$

where \hat{r}_{ui} is the estimated rating, K_u is the items rated by user u , $\text{ratings}(i)$ is the number of ratings for item i , and $\text{diff}(i, j)$ is the average difference in ratings for items i and j . While simplistic, Slope One is computationally effective and produces results comparable to more complex methods ([Lemire and Maclachlan, 2005](#), p5).

(2) *Neighborhood estimation* is part of many recommendation systems. It is the core principle behind most collaborative filtering algorithms, that estimate an unknown rating by averaging the ratings of similar items or users, weighted by this similarity. These approaches often work in two steps: First, a neighborhood of similar elements is computed. Second, the similarities and connections within this neighborhood is used to produce a prediction.

The principal method for computing user similarity is the *pearson correlation coefficient* (PCC) ([Segaran, 2007](#), p11). While simple, the PCC compares favorably to more complex approaches, and is often used as a benchmark for testing new ideas (e.g. in [Lemire and Maclachlan \(2005\)](#); [Ujii and Bentley \(2002\)](#); [Konstas et al. \(2009\)](#)).

The PCC is a statistical measure of the correlation between two variables. In our domain, the variables are two users, and their measurements are the ratings of co-rated items. The coefficient produces a value in the range $[-1, 1]$ where 1 signifies perfect correlation (equal ratings), 0 for no correlation and -1 for a negative correlation. The negative correlation can for example signify two users that have diametrically opposing tastes in movies. We compute PCC by dividing the covariances of the user ratings with their standard deviations:

$$\text{pcc}(u, v) = \frac{\text{cov}(R_u, R_v)}{\sigma_{R_u} \sigma_{R_v}}.$$

When expanding the terms for covariance and standard deviations, and using a limited

neighborhood size n , we get

$$\text{pcc}_n(u, v) = \frac{\sum_{i \in K}^n (R_{ui} - \bar{R}_u)(R_{vi} - \bar{R}_v)}{\sqrt{\sum_{i \in K}^n (R_{ui} - \bar{R}_u)^2} \sqrt{\sum_{i \in K}^n (R_{vi} - \bar{R}_v)^2}}.$$

The limited neighborhood size becomes the statistical sampling size, and is a useful way of placing an upper bound on the complexity of computing a neighborhood. n does not have to be a random sampling — it can also be limited by the number of ratings the two compared users have in common, the number of ratings each user have, or something similar, as denoted by K in our the formula.

After a neighborhood is determined, it is time to predict our desired rating. When using *collaborative* recommenders, this means averaging the neighborhood ratings weighted by similarity (Segaran, 2007, p16):

$$\bar{r}_{ui} = \frac{\sum_{v \in K(u, i)} \text{sim}(u, v) \times R_{vi}}{\sum_{v \in K(u, i)} \text{sim}(u, v)},$$

where $\text{sim}(u, v)$ is the similarity between two users, $K(u, i)$ is the set of users in the neighborhood of u that have rated item i . This is possible the simplest way of computing a neighborhood-based prediction. Most systems use more complex estimations. For instance, Koren (2008) uses the baseline ratings discussed above instead of plain user and item ratings, to remove what they call global effects where some users are generous or strict in their explicit preferences, and some items are consistently rated differently than the average.

Content-based recommenders based on neighborhoods work on similar principles. The difference is that we compute similarities between items, not users. The simplest approach is to find items highly rated by the current user, compute the neighborhood by finding items similar to these, and produce ratings by weighting the initial rating with the similarity of the neighboring items.

The PCC is but one of many methods used to compute neighborhoods. Other simple measures include the *euclidean distance* (Segaran, 2007, p10), Spearman’s or Kendall Tau rank correlation coefficients (Herlocker et al., 2004, p30) — variations on the PCC. Similarity metrics from information retrieval, such as *cosine correlation* from the *vector space model* (VSM) are also popular, often used to compute item similarities (see section 1.4).

Bell and Koren (2007b) shows a more sophisticated neighborhood estimation which computes global interpolation weights, that can be computed simultaneously for all nearest neighbors. Combinations of metrics are also possible. Ujjin and Bentley (2002) first use a simple euclidean metric to gather a larger neighborhood, which is then refined by a *genetic algorithm*. Another way of computing neighborhoods is by reducing the dimensions of the ratings matrix, as we will now introduce.

(3) *Dimensionality reduction* is an oft-used technique when creating recommender systems. The ratings matrix is factored into a set of lower dimension matrixes, that can be used to approximate the original matrix. Since this has the added effect of trying to approximate unknown cells, the lower dimension matrices can be used to predict unknown ratings (a type of least squares data fitting).

Singular Value Decomposition (SVD) is a common method for such matrix factorization (e.g. Billsus and Pazzani (1998, p5), Sun et al. (2005), Bell et al. (2007b)). This is the same underlying technique used by *latent semantic indexing* (LSI) in information retrieval (Baeza-Yates and Ribeiro-Neto, 1999, p44). Formally, SVD is the factorization $M = U\Sigma V^*$. M is an $m \times n$ matrix, in our case the ratings matrix, with m users and n items. U is an $m \times m$ factor (sometimes called the "hanger"), V^* (the conjugate transpose of V) is an $n \times n$ factor ("stretcher"). Σ is a $m \times n$ diagonal matrix ("aligner").

The dimensionality of the ratings space is performed by truncating the factor matrices each to a number of rows or columns, where the number is a parameter depending on the current domain and data. By truncating the factors, we in essence create a higher-level approximation of the original matrix that can identify latent features in the data. With the factors reduced to k dimensions, the result looks like this:

$$\begin{bmatrix} R_{m,n} \end{bmatrix} \Rightarrow \begin{bmatrix} U_{m,k} \end{bmatrix} \begin{bmatrix} \Sigma_{k,k} \end{bmatrix} \begin{bmatrix} V_{k,n}^* \end{bmatrix}$$

Two important transformations happen in this reduction. First, ratings that do not contribute to any greater pattern are removed as "noise". Second, ratings that in some way correlate to each other are enhanced, giving more weight to the actual predictive parts of the data. This means that the reduced factors can for instance identify features that correspond to correlations between items or users. These features are comparable to the mapping of terms to concepts in LSI.

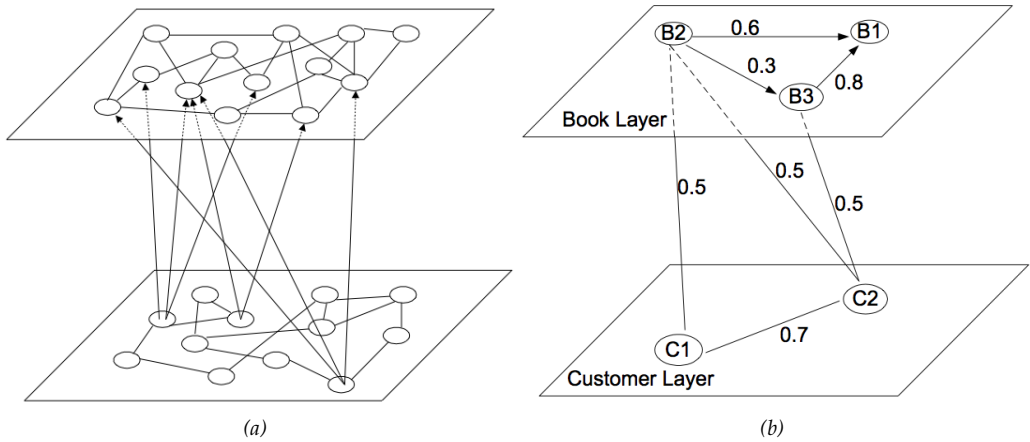


Figure 1.3: Network Traversal: (a) A graph with two kinds of nodes, e.g. items and users. (b) A graph with books and customers, where recommendations can be made by traversing the weighted connections. Connections between nodes of the same type represent similarity, while connections between books and customers represent purchases. Figures from [Huang et al. \(2002\)](#).

There are many ways of using the reduced factors. We can for instance use the resulting reduced factors to find similar users by their cosine similarity (see Section 1.4). We can of course also find similarities between items, clusters of items and user and so on, all based on latent "categories" discovered by the automatic identification of patterns in the data. SVD is then an ingenious way of dealing with the commonly sparse ratings data, by identifying latent correlations and patterns in the data, which is exactly what we need to predict unknown ratings or connections.

(4) *Network traversal* refers to estimating predictions by traversing a graph of users and items to provide recommendations. The connections between nodes can be any type of relation that makes sense to the RS. Examples include linking item and user nodes based on purchases or explicit ratings, linking user nodes from asymmetrical (directed edges) symmetrical (undirected edges) relations, or linking items based on some similarity metric.

[Huang et al. \(2002\)](#) used network traversal to create a simple system for recommending books to customers. Here, edges between items and users correspond to ratings, and edges connecting nodes of the same type are created by connecting elements that have similarity above a certain threshold. Predictions are generated by traversing the graph a preset number of steps starting at the current user, and multiplying the weights of paths leading to the target item (see Figure 1.3).

The complexity of recommender systems based on networks are only limited by the

kinds of relations we can produce. For example, recommending other users in social networks can easily utilize friend or friend-of-a-friend relations to find others the current user might be interested in connecting to. Indeed, any relevant similarity metric can be used to connect nodes of the same type, or nodes of different types.

One variation comes from [Walter et al. \(2008\)](#), who create a network of *transitive trust* to produce recommendations. Here, the neighborhood of users is determined by traversing through users connected by a level of trust. The trust can for example be a function of how many agreeable results the connection to a user has produced. In other words, users trust each others recommendations based on previous experience.

[Konstas et al. \(2009\)](#) takes yet another approach that measures the similarity between two nodes through their *random walks with restarts* (RWR) technique.

Starting from a node x , the RWR algorithm randomly follows a link to a neighboring node. In every step, there is a probability α that the algorithm will restart its random walk from the same node, x . A user-specific column vector $\mathbf{p}^{(t)}$ stores the long term probability rates of each node, where $\mathbf{p}_i^{(t)}$ represents the probability that the random walk at step t is at node i . \mathbf{S} is the column-normalized adjacency-matrix of the graph, i.e. the transition probability table. \mathbf{q} is a column vector of zeroes with a value of 1 at the starting node (that is, \mathbf{q}_i is 1 when the RWR algorithm starts at node x). The stationary probabilities of each node, signifying their long term visiting rate, is then given by

$$\mathbf{p}^{(t+1)} = (1 - \alpha)\mathbf{S}\mathbf{p}^{(t)} + \alpha\mathbf{q}$$

when it is run to convergence (within a small delta). Then, the *relatedness* of nodes x and y is given by \mathbf{p}_y where p is the user model for the user represented by node x . [Konstas et al.](#) found that this approach outperformed the PCC, as long as the social networks were an explicit part of the system in question. In other words, the connections between users had to be one actively created by the users to be of such quality and precision that accurate predictions could be made.

After this whirlwind tour of recommender systems, it is time to look at some closely related topics: information retrieval and personalized search. This will form the basis for the case study performed in the next chapter.

1.4 Personalized Search

Personalized search means adapting the results of a search engine to each individual user. As we shall see, this field has a lot in common with user modeling and recommender system. In both situations, we wish to predict how relevant an item will be to each user. Before delving into the techniques of personalizing search results, we present the basics of *information retrieval* (IR).

Information Retrieval

Manning et al. (2008, p1) define IR as "finding material (usually documents) of an unstructured nature (usually text) that satisfies an information need from within large collections (usually stored on computers)".

How does this relate to recommender systems? There is an important distinction: The purpose of *recommending* is twofold: (1) show the user items similar to another item, and (2) allow discovery of relevant items the user did not know exist. The purpose of *search* is a bit different: allow the user to find the location of information he or she knows (or hopes) exists. In other words, the defining separator is often the knowledge of existence.

However, as we shall see in this chapter, the two fields employ a lot of the same methods and terminology. In the next chapter, we will show how these can work together.

Baeza-Yates and Ribeiro-Neto (1999, p23) presents a formal definition of an IR system: $IR = (Documents, Queries, Framework, ranking(q_i, d_i))$

As evident by the scope of IR literature, these elements can be just about anything that has to do with retrieving information. However, in what is often called *classic IR*, the documents contain free text with little to no describing structure, and the queries are short user-initiated descriptions of an *information need* (Baeza-Yates and Ribeiro-Neto, 1999, p19). Among other domains, this model describes web search engines, where the documents are web pages and queries are short sentences or a few keywords input by users.

The *Framework* in our quadruple refers to how documents are stored and retrieved. Basic approaches to IR split each document into a set of terms (e.g. words), and create an inverted index (Manning et al., 2008, p22) that lists each document that each term appears in. There are numerous extensions to this framework, including:

- Positional information for phrase search (Manning et al., 2008, p39)
- Stop word removal (removing the most common terms) (Manning et al., 2008, p27)
- Stemming (reducing words to their root forms) (Manning et al., 2008, p32)
- Lemmatization (contextual inflection removal) (Manning et al., 2008, p32)
- Query reformulation (Baeza-Yates and Ribeiro-Neto, 1999, p117)

All these techniques help improve (among other things) the *recall* and *precision* of the retrieval engine. Recall, precision and relevance are well defined measures for evaluating the quality of a search engine (Manning et al., 2008, p5):

- A document is *relevant* if it satisfies the user's information need.
- *Recall* is the fraction of relevant documents retrieved by the system.
- *Precision* is the fraction of retrieved documents that are relevant.

There are many more measures, but these two succinctly define what a search engine must do to be successful: retrieve many relevant documents and few irrelevant documents. Failing this test is to neglect the main purpose of an IR: preventing information overload by allowing people efficient access to relevant parts of an otherwise overwhelming information repository.

To us, however, the most interesting part of any IR system is the *ranking function*. This function maps queries to documents by a scalar score, signifying how well a match each document is to a query. The relation to recommender systems should be self-evident, and indeed, IR systems use many of the same metrics to measure query/document similarity.

A common framework for storing and ranking documents is the previously mentioned vector space model (VSM). This model stores documents as term vectors. Each term represents a dimension, and documents are vectors in this term-space. When performing a query, the query terms are also represented as a vector in the same space. By computing the cosine similarity between the query and each document, we get a good estimate of how well a document matches a query (Baeza-Yates and Ribeiro-Neto, 1999, p29).

The next question is what to store at each (document, term) coordinate in the vector space (called the document-term weights). Storing simple 1 or 0 values representing whether or not terms are present gives a model where a document's relevance is proportional to how many of the query terms it includes. However, this is not very precise. For example, by this definition, a document containing every conceivable query term would be the most relevant to any query. A better idea is to use something like the TF-IDF weighting scheme (Baeza-Yates and Ribeiro-Neto, 1999, p29):

$$w_{t,d} = tf_{t,d} \times idf_t = \frac{\text{freq}(t,d)}{\sum_{k \in d} \text{freq}(k,d)} \times \log \frac{N}{n_t}.$$

The final weight is computed by multiplying the term frequency score (TF) $tf_{t,d}$ with the inverse document frequency (IDF) idf_t . TF evaluates how well the term describes the document contents, while IDF punishes terms that appear in many documents. $\text{freq}_{t,d}$ gives the frequency of a term in a document. N is the total number of documents, and n_t the number of documents in which t appears. The effect of the IDF factor is dampened by taking its log-value. Together, TF and IDF ranks documents higher by words that discriminate well within the document corpus, and ignores words that appear in so many documents that they have little to no predictive capacity.

While simple, TF-IDF has proven itself resilient when compared to more complex methods, and many more complex methods have been built on its foundations (e.g. BM25, one of the most successful probabilistic weighting algorithms (Robertson, 2010)).

There are as many IR models as there are domains that need search, and even the basic vector space model can be constructed in a myriad of ways. There is also the simpler *boolean search model*, where queries are based on boolean algebra. Probabilistic models frame the similarity question as the probability that the document is relevant. Latent Semantic Indexing (LSI), the application of SVD to IR by performing dimensionality reduction of the term-space into concept-space is another approach. See Manning et al. (2008), Robertson (2010) or Baeza-Yates and Ribeiro-Neto (1999) for a more comprehensive introduction to models in IR.

The important take-away is that, while serving different use cases, RSs and IR systems employ much of the same technology with different input and expected output.

Signals

Modern web search engines have long ago moved on from simple ranking metrics such as TF-IDF. While similar traditional metrics may form the foundation of modern search engines, a lot more thought goes into the final results. Different types of rankings are combined to produce the final *search engine results page* (SERP), with each ranking function often being referred to as a *signal*. Alternate names include *reranking* or *rescoring* functions.

Google, the company behind the popular online search engine, writes: "Today we use more than 200 signals, including PageRank, to order websites, and we update these

algorithms on a weekly basis. For example, we offer personalized search results based on your web history and location."¹ Bing, another popular search engine, uses the same terminology: "We use over 1,000 different signals and features in our ranking algorithm."²

Signals are often products of the document structure of the current domain. [Sergey and Lawrence \(1998, p5\)](#) points to the use of the proximity of query terms in matching documents. Those where the terms appear close together are natural candidates for a higher ranking. Other signals, still reliant on the documents themselves, are more domain oriented. Another signal they point out is how words in a larger or bold font can be weighted higher than normally typeset words.

Signals can also depend on the query. [Manning et al. \(2008, p145\)](#) describes a system that takes multi-word queries, breaks them up into different permutations and runs each new query against the same document index and ranking function. Each query corresponds to its own ranked set of results, which are sent to a *rank aggregation function* which turns the accumulated ranking evidence into one coherent result. We will have more to say on rank aggregation in Section 1.5.

Signals can also be external to the collection or relational within the collection. PageRank ([Sergey and Lawrence, 1998, p4](#)) is perhaps the most known of the relational signals. The algorithm forms a probability distribution over web pages, ranking their perceived authority or importance according to a simple iterative estimation. Each web site is given its rank based on how many pages that link to it. For each page that provides links, the score it contributes to the linked-to page is its own page rank weighted inversely proportional to the number of outbound links the page has. Another intuitive justification for a site's PageRank is the *random surfer model* ([Sergey and Lawrence, 1998, p4](#)). The probability that the random surfer visits a page is its PageRank. The "randomness" is introduced by a damping parameter d , which is the probability that a user will stop browsing and start at a new random page:

$$\text{PageRank}(x) = \frac{1-d}{N} + d \sum_{y \in B_x} \frac{\text{PageRank}(y)}{\text{Links}(y)},$$

where B_x is the set of pages linking to page x , and $\text{Links}(y)$ is the number of outbound links from page y . The first term distributes an equal pagerank score to all pages that have no outbound links, as N is the total number of pages. This iterative algorithm is run until convergence inside a small delta.

(1) google.com/corporate/tech.html — accessed 11/04/2011

(2) bing.com/community/site_blogs/b/search/archive/2011/02/01/thoughts-on-search-quality.aspx — accessed 11/04/2011

Let us now finally take a look at one of the main uses of signals: *personalized search*.

Personalization of Search Results

Search engines, especially online search engines, face a huge challenge. In addition to the wide range of websites, the ambiguity of language, the restricted nature of queries, comes the wildly differing users. Each user is unique. Even when considering one user, there might be many different use cases, for example when using the same search engine at work and at home. Another identified problem is that users use search engines for navigation as well as pure search. Teevan et al. (2007) found that as many as 40% of all queries to the Yahoo! search engine were "re-finding queries", i.e. attempts to find information the user had accessed before.

Personalized search (PS) attempts to solve these problems by introducing individually catered search results. These techniques are based on user modeling (as introduced in Section 1.2), and attempts to build predictive models based on mined user preferences. Commonly, this is done through query log analysis (e.g. Liu et al. (2002); Sugiyama et al. (2004); Shen et al. (2005); Speretta and Gauch (2000)) In other words, these are often model-based techniques with implicit knowledge gathering agents, that create individual, long-term user models (see Section 1.3).

To demonstrate how these methods compare to traditional recommendation systems, we will explore a few different approaches to personalized search: (1) *personalized topic-sensitive PageRank*, (2) *folksonomy-based personalization* and (3) *social network search ranking*.

(1) Haveliwala (2003) introduced a topic-sensitive PageRank algorithm, that they found to be "generate more accurate rankings than with a single, generic PageRank vector". In essence, they create topic-specific PageRank vectors for a number of pre-set topics, creating many rankings per page, one for each topic. This new PageRank is computed based on an existing set of websites that belong to each topic. Qiu and Cho (2006) achieved "significant improvements" to this approach by adding a personally adaptive layer to the topic-sensitive PageRank algorithm, creating a *personalized PageRank algorithm*.

In addition to the topic vector, Qiu and Cho creates a topic-preference vector for each user. When the user has clicked on a few search results, a learning algorithm kicks in and estimates approximately how likely the user is to be interested in each of the pre-set topics, creating the topic-preference vector T . When it is time to rank a page p in response to the query q , they compute the personalized ranking:

$$PersonalizedRanking(T, p, q) = \sum_{i=1}^m T(i) \times Pr(q|T(i)) \times TSPR_i(p)$$

We will not deduce this equation here (see [Qiu and Cho \(2006, p5\)](#)), but let us explain it. T is the user-specific topic preference vector. i is the index of a topic and m the total number of topics. $Pr(q|T(i))$ is the probability that the query belongs in topic i . This can be as simple as the total number of times the query terms appear in websites under topic i . $TSPR_i(p)$ is the topic-sensitive PageRank score for page p in topic i . Basically, this is the normal PageRank vector computed within a pre-set topic i .

The construction of $T(i)$, i.e. the training phase of the algorithm, is performed by mining the query logs for each user. By identifying how many sites the user has visited in each topic, computing T can be done through linear regression or by using a Maximum-likelihood estimator (basically, any method that can fit a curve). [Qiu and Cho \(2006, p10\)](#) reports improvements of 25% to 33% over the Topic-sensitive PageRank approach, which [Haveliwala \(2003\)](#) reports outperformed the original PageRank algorithm.

(2) Web applications often have more information about users and items (documents, sites or articles) than simple ratings. One of these extra resources are tags, simple keywords assigned from users to items. The collection of users, items, tags and user-based assignment of tags to resources is called a *folksonomy*.

[Hotho et al. \(2006\)](#) defines a folksonomy as a tuple $F = (U, T, R, Y, \prec)$. Here, U , T and R are finite sets of users, tags and resources (items), respectively. Y is a ternary relation between users, tags and resources, called tag assignments. \prec is a user-specific tag hierarchy, applicable if the tags are organized as super- and sub-tags. The *personomy* P_u is a user-specific part of F , i.e. the tags, items and assignments related to one user u . In our terms, this personomy would be the user model. [Hotho et al.](#) use folksonomies to do information retrieval based on their *FolkRank* search algorithm, a derivative of PageRank.

[Bao et al. \(2007\)](#) shows how folksonomies can be used to personalize search. They first create a topic-space, where every user and document are represented. Each tag in the system is a dimension in this topic-space, or tag-space. Whenever a new query is issued, two things happen: First, a regular IR method computed a standard, non-personalized ranking of documents. Second, a personalized ranking list is computed by performing a simple vector-space model matching in the topic-space, for example by using cosine similarity (as previously explained). The personalized list is then unrelated to the actual query, and is simply a ranking of the most relevant pages to the current user.

The two ranks are aggregated by a simple consensus-metric, the *weighted borda-fuse* (WBS) aggregator (Xu et al., 2008, p3), which is nothing more than a weighted combination of the rankings:

$$\text{rank}(u, q, p) = \alpha \cdot \text{rank}_{IR}(q, p) + (1 - \alpha) \cdot \text{rank}_{personal}(u, p)$$

Xu et al. tried many combinations of weights, topic selection and datasets, with the general conclusion that folksonomy-based personalized search has great potential. If nothing else, this example shows how easily tags can be integrated to provide an individual searching experience.

(3) Carmel et al. (2009) developed a personalized search algorithm based on a user's *social network*. By re-ranking documents according to their relation to with individuals in the current user's social network, they arrived at a document ranking that "significantly outperformed" non-personalized social search (Carmel et al., 2009, p1). Note, however the qualifier "social search" — their project searches through social data within an enterprise, naturally conducive to algorithmic alterations based on social concepts. However, as social data is data just as well, seeing how a personalized approach improves standard IR in this domain, is helpful.

Their approach: First, documents are retrieved by a standard IR method. Second, the user's socially connected peers are also retrieved. Third, the initial ranked list of documents is re-ranked based on how strongly they are connected to the user's peers, and how strongly those peers are connected to the user. The user-user similarity is computed based on a few signals (Carmel et al., 2009, p2), e.g. co-authoring of documents, the use of similar tags (see (2)) or commenting on the same content. The user model also includes a list of terms the current user has employed in a social context (profile, tags, et cetera). This is all done to infer implicit similarity based on social connections.

The algorithm is quite powerful, and combines three types of rankings: The initial IR score, the social connection score, and a term score, where the terms are tags and keywords used by a user. The user model is $U(u) = (N(u), T(u))$, where $N(u)$ are the social connections of u and $T(u)$ the user's profile terms. First, the score based on connections and terms is computed, weighted by β which determines the weighting of both approaches:

$$S_P(q, d|U(u)) = \beta \sum_{v \in N(u)} w(u, v) \times w(v, d) + (1 - \beta) \sum_{t \in T(u)} w(u, t) \times w(t, d)$$

Finally, the results are combined with the ranking returned by the IR method (R_{IR}). A parameter α is used to control how much each method is weighted:

$$S(q, d|P(u)) = \alpha R_{IR}(q, d) + (1 - \alpha) S_P(q, d|U(u))$$

This approach, while simple, shows how social relations and social annotations can easily be used to personalize a search experience. However, Carmel et al. (2009, p10) notes that the high quality data in their enterprise setting were important to achieve the improved results.

1.5 Aggregate Modeling

So far we have seen a lot of modeling methods, both for recommender systems (RS) and for personalized search (PS). *Aggregate modeling* (AM) is the act of merging two or more modeling methods in some way. A proper aggregation method creates a combined result that is better than either of the individual methods. In other words, the sum is greater than the parts. We have already seen a few examples of aggregate modeling:

- Koren (2008) aggregates global, individual and per-item averages to a baseline.
- Huang et al. (2002) aggregates different types of graph relations into one prediction.
- Haveliwala (2003) combined their personalized PageRank with another approach.
- Carmel et al. (2009) combined classic IR with social relations and annotations.

Clearly, aggregation is an important part of both RS and PS. The reasoning behind combining different approaches is that no one methods can capture all the predictive nature of the available data. For example, Bell et al. (2007a) created a recommender systems where the neighborhood- and SVD-based approaches complement each other. While the neighborhoods correspond to "local effects" where similar users influence each other's predictions, the dimensionality reduction finds "regional effects", major structural patterns in the data. As they say: "Both the local and the regional approaches, and in particular their combination through a unifying model, compare favorably with other approaches and deliver substantially better results than the commercial Netflix Cinematch recommender system ..." (Bell et al., 2007a, p1)

Early approaches in recommender systems dabbled in aggregating content-based and collaborative approaches. Claypool et al. (1999) combined the two approaches in an

effort to thwart problems with each method. Collaborative filtering (CF) methods have problems rating items for new users, radically different users or when dealing with very sparse data. Content-based (CB) methods do not have the same problems, but are less effective than CF in the long run, as CB does not tap into the knowledge of other users in the system — knowledge that out-performs simple content analysis. In [Claypool et al. \(1999\)](#), the two types of recommenders were used to create a simple weighted result.

So, are all hybrid recommenders aggregation based? This is mostly a question of semantics and implementation. ([Burke, 2007](#), p4) defines a hybrid system as "any recommender system that combines multiple recommendation techniques together to produce its output." Some hybrid methods combine stand-alone methods, and are definitely aggregations. Other methods merge the methods themselves into one implementation that uses the data in different ways. ([Burke, 2007](#), p4) describes a few types of hybrid recommenders:

- Weighted combinations of recommenders.
- Switching and choosing one recommender in different contexts.
- Mixing the outputs and presenting the result to each user.
- Cascading, or prioritized recommenders applied in succession.
- Augmentation, where one recommender produces input to the next.

However, without being too pedantic, these can all be seen as aggregate approaches: Multiple prediction techniques are used to create a result better than any single methods would provide.

[Bell et al. \(2007b\)](#) took method aggregation to its logical conclusion when winning the Netflix Challenge, by combining 107 individual results from different recommenders: "We strongly believe that the success of an ensemble approach depends on the ability of its various predictors to expose different, complementing aspects of the data. Experience shows that this is very different from optimizing the accuracy of each individual predictor. Quite frequently we have found that the more accurate predictors are less useful within the full blend." ([Bell et al., 2007b](#), p6) In other words, the final result is improved because of the disjoint reasoning performed by the different predictors.

There are two main approaches to model aggregation ([Liu et al., 2007](#), p1):

1. Rank (or *order-based*) aggregation (RA) lets each method produce a sorted list of recommendations or search results. These lists are then combined into one final list, through some aggregation method (see [Dwork et al. \(2001\)](#) or [Klementiev et al.](#)

(2008)). These methods only require the resulting list of items from each method (Aslam and Montague, 2001, p1).

2. Prediction (or *score-based*) aggregation (PA) works on the item- or user-level by combining predicted scores one-by-one, creating an aggregated result for each element that should be evaluated. These methods require the actual prediction scores for any item from each method (Aslam and Montague, 2001, p2).

Rank Aggregation

RA combines multiple result lists into one list by some metric. Dwork et al. (2001) shows a few metrics applicable to meta-search, the combination of results from multiple search engines. Borda's method (Dwork et al., 2001, p6) is based on positional voting, where each result gets a certain number of points from each result set, based on where it appears in the sorted list. Items at the top gets the most points, while lower items gets fewer points. This is in essence a method where each method has a set number of votes (c , the number of results) that they give to each item.

As we saw in Section 1.4, Xu et al. (2008, p3) used a weighted version of this approach to combine an IR and personal approach to result ranking. Aslam and Montague (2001, p3) calls their version of this *Weighted Borda-Fuse*, where the points given from a method to an item is controlled by the weights estimated for each method. Aslam and Montague (2001, p4) also explain a bayesian approach (*bayes-fuse*), that combined with the *naive Bayes* independence assumption produce the following formula:

$$\text{relevance}(d) = \sum_{i \in \text{Methods}} \log \frac{\Pr(r_i(d)|rel)}{\Pr(r_i(d)|irr)}.$$

Here, $\Pr(r_i(d)|rel)$ is the probability that document d is relevant given its ranking by method i . Conversely, $\Pr(r_i(d)|irr)$ is the probability that the document is irrelevant. The probability values are obtained through training, and evaluating the results against known relevance judgements. Their results were positive: "Our experimental results show that metasearch algorithms based on the Borda and Bayesian models usually outperform the best input system and are competitive with, and often outperform, existing metasearch strategies." Aslam and Montague (2001, p1).

Rank aggregation is a substantial topic, with many approaches. The main take-away is that this approach combines list of results into one single results, and experiments show

that results superior to the best of the combined methods are attainable. See [Aslam and Montague \(2001\)](#), [Liu et al. \(2007\)](#) or [Klementiev et al. \(2008\)](#) for more information.

Prediction Aggregation

For personalized search (speculation)

Explain next chapter

Rank aggregation for the web: [Dwork et al. \(2001\)](#)

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