



Advances and challenges in conversational recommender systems: A survey

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ARTICLE INFO

Keywords:

Conversational recommendation system

Interactive recommendation

Preference elicitation

Multi-turn conversation strategy

Exploration-exploitation

ABSTRACT

Recommender systems exploit interaction history to estimate user preference, having been heavily used in a wide range of industry applications. However, static recommendation models are difficult to answer two important questions well due to inherent shortcomings: (a) What exactly does a user like? (b) Why does a user like an item? The shortcomings are due to the way that static models learn user preference, i.e., without explicit instructions and active feedback from users. The recent rise of conversational recommender systems (CRSs) changes this situation fundamentally. In a CRS, users and the system can dynamically communicate through natural language interactions, which provide unprecedented opportunities to explicitly obtain the exact preference of users. Considerable efforts, spread across disparate settings and applications, have been put into developing CRSs. Existing models, technologies, and evaluation methods for CRSs are far from mature. In this paper, we provide a systematic review of the techniques used in current CRSs. We summarize the key challenges of developing CRSs in five directions: (1) Question-based user preference elicitation. (2) Multi-turn conversational recommendation strategies. (3) Dialogue understanding and generation. (4) Exploitation-exploration trade-offs. (5) Evaluation and user simulation. These research directions involve multiple research fields like information retrieval (IR), natural language processing (NLP), and human-computer interaction (HCI). Based on these research directions, we discuss some future challenges and opportunities. We provide a road map for researchers from multiple communities to get started in this area. We hope this survey can help to identify and address challenges in CRSs and inspire future research.

1. Introduction

Recommender systems have become an indispensable tool for information seeking. Companies such as Amazon and Alibaba, in e-commerce, Facebook and Wechat, in social networking, Instagram and Pinterest, in content sharing, and YouTube and Netflix, in multimedia services, all have the need to properly link items (e.g., products, posts, and movies) to users. An effective recommender system that is both accurate and timely can help users find the desired information and bring significant value to the business. Therefore, the development of recommendation techniques continues to attract academic and industrial attention.

Traditional recommender systems, which we call *static recommendation models* in this survey, primarily predict a user's preference

towards an item by analyzing past behaviors offline, e.g., click history, visit log, ratings on items. Early methods, such as collaborative filtering (CF) (Sarwar et al., 2001; Schafer et al., 2007), logistic regression (LR) (Nelder and Wedderburn, 1972), factorization machine (FM) (Rendle, 2010), and gradient boosting decision tree (GBDT) (Ke et al., 2017), have been intensively used in practical applications due to the efficiency and interpretability. Recently, more complicated but powerful neural networks have been developed, including Wide & Deep (Cheng et al., 2016), neural collaborative filtering (NCF) (He et al., 2017), deep interest network (DIN) (Zhou et al., 2018a), tree-based deep model (TDM) (Zhu et al., 2018), and graph convolutional networks (GCNs) (Ying et al., 2018; Wu et al., 2019b; He et al., 2020).

Inherent Disadvantages of Static Recommendations. Static recommendation models are typically trained offline on historical

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behavior data, which are then used to serve users online (Covington et al., 2016). Despite their wide usage, they fail to answer two important questions:

1. *What exactly does a user like?* The learning process of static models is usually conducted on historical data, which may be sparse and noisy. Moreover, a basic assumption of static models is that all historical interactions represent user preference. Such a paradigm raises critical issues. First, users might not like the items they chose, as they may make wrong decisions (Wang et al., 2020a, 2020b). Second, the preference of a user may drift over time, which means that a user's attitudes towards items may change, and capturing the drifted preference from past data is even harder (Jagerman et al., 2019). In addition, for cold users who have few historical interactions, modeling their preferences from data is difficult (LeeJinbae et al., 2019). Sometimes, even the users themselves are not sure of what they want before being informed of the available options (Wang and Benbasat, 2013). In short, a static model can hardly capture the precise preference of a user.
2. *Why does a user like an item?* Figuring out why a user likes an item is essential to improve recommender model mechanisms and thus increase their ability to capture user preference. There are many factors affecting a user's decisions in real life (MaChang et al., 2019; Cen et al., 2020; Gao et al., 2019c). For example, a user might purchase a product because of curiosity or being influenced by others (Yu et al., 2019a). Or it may be the outcome of deliberate consideration. It is common that different users purchase the same product but their motivations are different. Thus, treating different users equally or treating different interactions by the same user equally, is not appropriate for a recommendation model. In reality, it is hard for a static model to disentangle different reasons behind a user's consumption behavior.

Even though much effort has been done to eliminate these problems, they make limited assumptions. For example, a common setting is to exploit a large amount of auxiliary data (e.g., social networks, knowledge graphs) to better interpret user intention (Shi et al., 2014). However, these additional data may also be incomplete and noisy in real applications. We believe the key difficulty stems from the inherent mechanism: the static mode of interaction modeling fundamentally limits the way in which user intention can be expressed, causing an asymmetric information barrier between users and machines.

Introduction of CRSs. The emergence of conversational recommender systems (CRSs) changes this situation in profound ways. There is no widely accepted definition of CRS. In this paper, we define a CRS to be:

A recommendation system that can elicit the dynamic preferences of users and take actions based on their current needs through real-time multi-turn interactions.

Our definition highlights a property of CRSs: *multi-turn interactions*. By a narrow definition, conversation means multi-turn dialogues in the form of written or spoken natural language; from a broader perspective, conversation means any form of interactions between users and systems, including written or spoken natural language, form fields, buttons, and even gestures (Jannach et al., 2020). Conversational interaction is a natural solution to the long-standing asymmetry problem in information seeking. Through interactions, CRSs can easily elicit the current preference of a user and understand the motivations behind a consumption behavior. Fig. 1 shows an example of a CRS where a user resorts to the agent for music suggestions. Combining the user's previous preference (loving Jay Chou's songs) and the intention elicited through conversational interactions, the system can offer desired recommendations easily. Even if the produced recommendations do not satisfy the user, the system has chances to change recommendations based on user

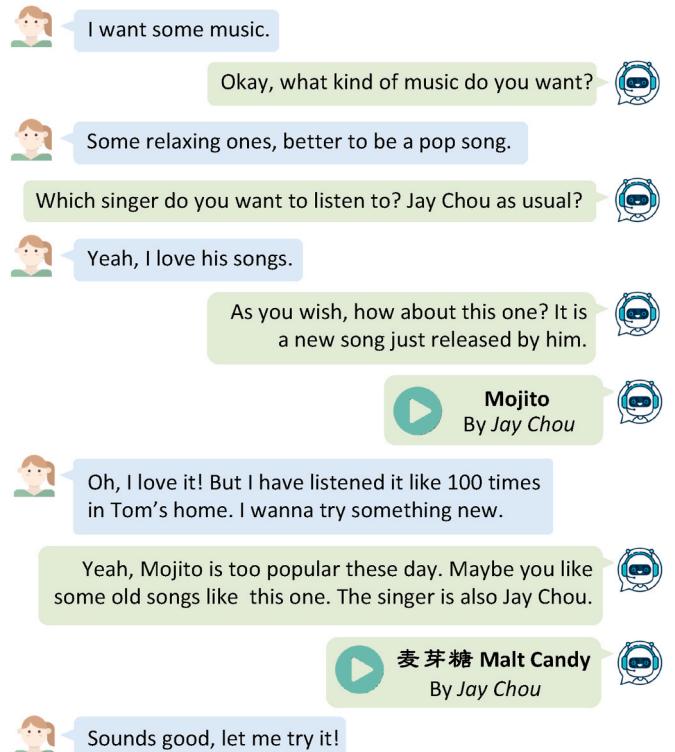


Fig. 1. A toy example of a conversational recommender system in music recommendation.

feedback.

Recently, attracted by the power of CRSs, many researchers have been on focusing on exploring this topic. These efforts are spread across a broad range of task formulation, in diverse settings and application scenarios. We collect the papers related to CRSs by searching for “Conversation* Recommend*” on DBLP¹ and visualize the statistics of them with regard to the published year and venue in Fig. 2. There are 148 unique publications up to 2020, and we only visualize the top 10 venues, which contain 53 papers out of all 148 papers at all 89 venues. It is necessary to summarize these studies which put efforts into different aspects of CRSs.

Connections with Interactive Recommendations. Since the birth of recommender systems, researchers have realized the importance of the human-machine interaction. Some studies propose interactive recommender systems (He et al., 2016; Wang et al., 2017; Chen et al., 2019ba; Zhou et al., 2020d) and critiquing-based recommender systems (Tou et al., 1982; Tversky and Simonson, 1993; Burke et al., 1997; Smyth and McGinty, 2003; Pu and Faltings, 2004; Chen and Pu, 2012; Luo et al., 2020b; LuoScott et al., 2020), which can be viewed as early forms of CRSs since they focus on improving the recommendation strategy online by leveraging real-time user feedback on previously recommended items.

In the setting of interactive recommendations, each recommendation is followed by a feedback signal indicating whether and how much the user likes this recommendation. However, interactive recommendations suffer from low efficiency, as there are too many items. An intuitive solution is to leverage attribute information of items, which is self-explanatory for understanding users' intention and can quickly narrow down candidate items. The critiquing-based recommender system is such a solution that is designed to elicit users' feedback on certain attributes, rather than items. Critiquing is like a salesperson who collects

¹ https://dblp.org/search?q=conversation*%20recommend*.

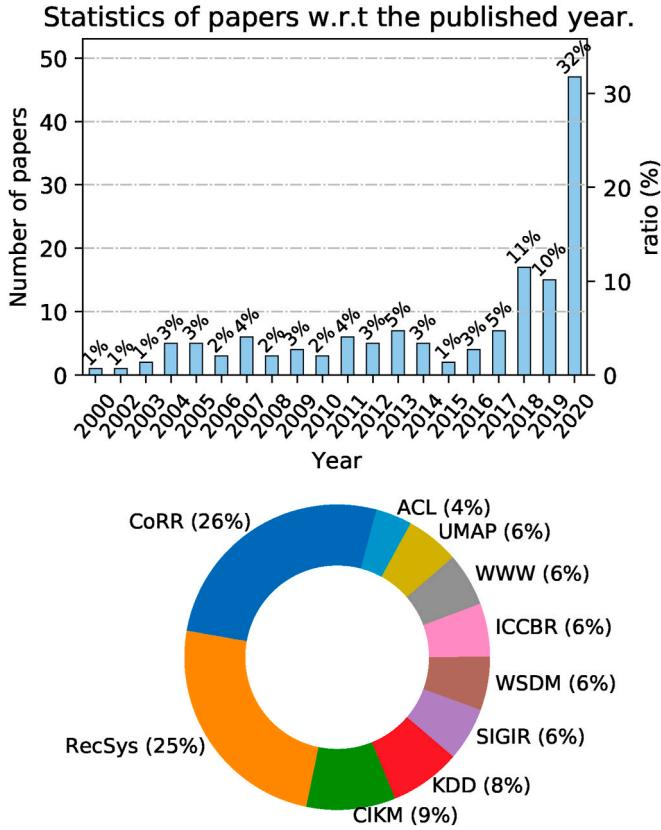


Fig. 2. Statistics of the publications related to CRSs, grouped by the publication year and venue. Only the top 10 venues are used in the visualization.

user preference by asking questions proactively on item attributes. For example, when seeking mobile phones, a user may follow the hint of the system and provides feedback such as “cheaper” or “longer battery life.” Based on such feedback, the system will recommend more appropriate items; this procedure repeats several times until the user finds satisfactory items or gives up. The mechanism gives the system an improved ability to infer user preference and helps quickly narrow down recommendation candidates.

Though effective, existing interactive and critiquing methods have a limitation: the model makes a recommendation each time after receiving user feedback, which should be avoided as the recommendation should only be made when the confidence is high. This problem is solved in some CRSs by developing a conversation strategy determining when to ask and recommend (Lei et al., 2020a, 2020b). Besides, the interactive and critiquing methods are constrained by their representation ability since users can only interact with the system through a few predefined options. The integration of a conversational module in CRSs allows for

more flexible forms of interaction, e.g., in the form of tags (Christakopoulou et al., 2018), template utterances (Sun and Zhang, 2018), or free natural language (Li et al., 2018). Undoubtedly, user intention can be more naturally expressed and comprehended through a conversational module.

Connections with Other Conversational AI Systems. Besides CRSs, there are other conversational AI systems, e.g., task-oriented dialogue systems (Chen et al., 2017; Zhang et al., 2020b; Pei et al., 2021), social chatbots (Ma et al., 2021; Li et al., 2021a; Wu and Yan, 2018), conversational searching (Voskarides et al., 2020; Rosset et al., 2020; Ren et al., 2021), and conversational question answering (QA) (Zhu et al., 2021). The common point of them is to utilize natural language as a powerful tool to convey information and thus to provide a natural user interface. Though these research topics all possess the keyword “conversation”, the central tasks are different. For example, while task-oriented dialogue systems aim to fulfill a certain task in human-machine dialogue, the concentration of effort is mainly on handling information in the textual language-based dialogue, e.g., natural language understanding (NLU), dialogue state tracking (DST), dialogue policy learning (DPL), and natural language generation (NLG) (Chen et al., 2017; Zhang et al., 2020b; Gao et al., 2019a). In CRSs, however, the multi-turn conversation can be built on any form of interaction (e.g., form fields, buttons, and even gestures (Jannach et al., 2020)) instead of merely textual form. Because CRSs concentrate on recommendation logic, the textual dialogue is just one possible means to convey information, i.e., it is auxiliary, not necessary. Although there are some CRSs implemented as end-to-end dialogue systems (Li et al., 2018; Chen et al., 2019bb), the human evaluation conducted by Jannach and Manzoor (2020) suggests the performance is not ideal and more efforts should be put on improving both recommendation and language generation.

Other conversational AI systems can also be distinguished from CRSs by their specific scenarios. For instance, conversational searching focuses on analyzing the input query (in contrast to eliciting user preference in CRSs); conversational QA focuses on the single-turn question answering (in contrast to multi-turn interaction in CRSs). Therefore, it is essential to identify the central tasks and primary challenges in CRSs to help the beginner and future researchers set foot in this field and keep up with state-of-the-art technologies.

Focuses of This Survey. Although many studies have been done on CRSs, there is no uniform task formulation. In this survey, we present all CRSs as the general framework that consists of three decoupled components illustrated in Fig. 3. Specifically, a CRS is made of a user interface, a conversation strategy module, and a recommendation engine. The user interface serves as a translator between the user and machine; generally, it extracts information from raw utterances of the user and transforms the information into machine-understandable representation, and it generates meaningful responses to the user based on the conversation strategy. The conversation strategy module is the brain of the CRS and coordinates the other two components; it decides the core logic of the CRS such as eliciting user preference, maintaining multi-turn

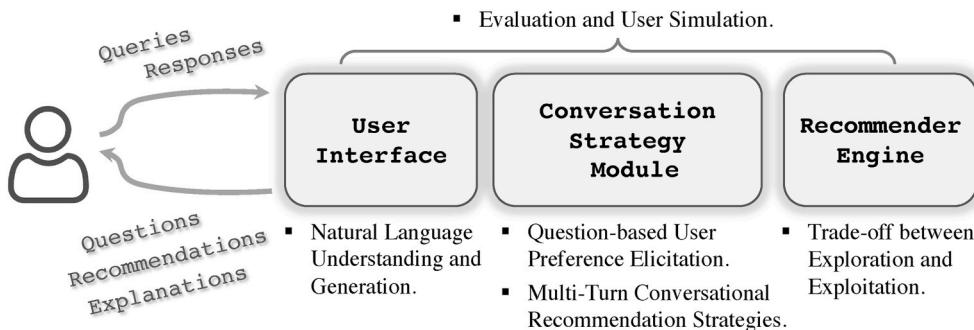


Fig. 3. Illustration of the general framework of CRSs and our identified five primary challenges on the three main components.

conversations, and leading new topics. The recommendation engine is responsible for modeling relationships among entities (e.g., the user-item interaction or item-item linkage), learning and recording user preference on items and attributes of items, retrieving the required information.

There are many challenges in the three components, we summarize five main challenges as following.

- **Question-based User Preference Elicitation.** CRSs provide the opportunity to explicitly elicit user preference by asking questions. Two important questions are needed to be answered: (1) What to ask? (2) **How to adjust the recommendations based on user response?** The former focuses on constructing questions to elicit as much information as possible; the latter leverages the information in user response to make more appropriate recommendations.
- **Multi-turn Conversational Recommendation Strategies.** The system needs to repeatedly interact with a user and adapts to the user's response dynamically in multiple turns. An effective strategy concerns when to ask questions and when to make recommendations, i.e., let the model choose between (1) continuing to ask questions so as to further reduce preference uncertainty, and (2) generating a recommendation based on estimation of current user preference. Generally, the system should aim at a successful recommendation using the least number of turns, as users will lose their patience after too many turns (Lei et al., 2020a). Furthermore, some sophisticated conversational strategies try to proactively lead dialogues (Wu et al., 2019; Balaraman and Magnini, 2020), which can introduce diverse topics and tasks in CRSs (Liu et al., 2020ab; Zhou et al., 2020c; Lewis et al., 2017; Wang et al., 2019).
- **Natural Language Understanding and Generation.** Communicating like a human being continues to be one of the hardest challenges in CRSs. For understanding user interests and intentions, some CRS methods define the model input as pre-defined tags that capture semantic information and user preferences (Christakopoulou et al., 2018; Lei et al., 2020a, 2020b; Zou et al., 2020). Some methods extract the semantic information from users' raw utterances via slot filling techniques and represent user intents in slot-value pairs (Zhang et al., 2018; Sun and Zhang, 2018; Ren et al., 2020). And for generating human-understandable responses, CRSs use many strategies such as directly providing a recommendation list (Zou et al., 2020; Zhang et al., 2018), incorporating recommended items in a rule-based natural language template (Sun and Zhang, 2018; Lei et al., 2020a, 2020b). Moreover, some researchers propose the end-to-end framework to enable CRSs to precisely understand users' sentiment and intentions from the raw natural language and to generate readable, fluent, consistent, and meaningful natural language responses (Li et al., 2018; Liu et al., 2020ab; Ren et al., 2020; Chen et al., 2019bb; Zhou et al., 2020a).
- **Trade-offs between Exploration and Exploitation (E&E).** One problem of recommender systems is that each user can only interact with a few items out of the entire dataset. A large number of items that a user may be interested in will remain unseen by the user. For cold-start users (who have just joined the system and have zero or very few interactions), the problem is especially severe. Thanks to the interactive nature, CRSs can actively explore the unseen items to better capture the user preference. In this way, users can benefit from having chances to express their intentions and obtain better-personalized recommendations. However, the process of exploration comes at a price. As users only have limited time and energy to interact with the system, a failed exploration will waste time and lose the opportunity to make accurate recommendations. Moreover, exposing unrelated items hurts user preference, compared to exploiting the already captured preference by recommending the items of high confidence (Schnabel et al., 2018; Li et al., 2015;

Gilotte et al., 2018). Therefore, pursuing E&E trade-offs is a critical issue in CRSs.

- **Evaluation and User Simulation.** Evaluation is an important topic. Unlike static recommender models that are optimized on offline data, CRSs emphasize the user experience during dynamic interactions. Hence, we should not only consider the turn-level evaluation for both recommendation and response generation but also pay attention to the conversation-level evaluation. Besides, evaluating CRSs requires a large number of online user interactions, which are expensive to obtain (Li et al., 2015; Jagerman et al., 2019; Huang et al., 2020). Practical solutions include: (1) leveraging the off-policy evaluation which assesses the target policy using the logged data under the behavior policy (Gilotte et al., 2018; Jagerman et al., 2019), and (2) directly introducing user simulators to replace the true users in evaluation (Zhang and Balog, 2020; Sun et al., 2021).

The five challenges are allocated to the corresponding component as illustrated in Fig. 3, where trading off the E&E balance is exclusive to the recommender engine; handling natural language understanding and generation is exclusive to the conversation module. The rest three challenges are related to both the components. We illustrate in Table 1 the solutions of some classic CRSs that focus on these directions. Limited by space, we only give part of the classic studies here. We will further discuss existing solutions in the following sections.

Differences with Existing Related Surveys. Recently, A number of related survey papers have been published. There are survey papers focusing on certain cutting-edge aspects in recommender systems, such as the bias issues and debiasing methods (Chen et al., 2020a), explainability/interpretability (Zhang and Chen, 2020), evaluation issues (Silveira et al., 2019), and novel methods that leverage deep neural networks (Wu et al., 2020, 2021; Zhang et al., 2019a), knowledge graphs (Guo et al., 2020), or reinforcement learning (Afsar et al., 2021) to improve the ability of recommendation systems. Also, there are survey papers that summarize new frontiers in conversational AI systems, such as the advanced methods (Chen et al., 2017; Gao et al., 2019a; Zhang et al., 2020b) and the evaluation issues (Celikyilmaz et al., 2020; Deriu et al., 2021) in dialogue systems. However, there is only one survey paper published in 2020 that focuses on CRSs (Jannach et al., 2020).

Jannach et al. (2020), for the first time, delved into different aspects of CRSs and made a comprehensive survey of CRSs. Specifically, they categorize existing CRSs in various dimensions, for instance, in terms of interaction modalities (e.g., buttons or written language), supported tasks (e.g., recommend or explain), or the knowledge CRSs use in the background (e.g., item-related information or dialogue corpora). Their survey provides a structured description of the CRS. Therefore, the audience, after reading this survey, can answer *what a CRS is*, for example, what the input/output or the functions of a CRS are. However, they may be still unsure about *what the key challenges are*, or *what to do next*. In our survey, we not only give the review of the current progress on CRSs including the existing assumptions and exploration but also refine the problems in state-of-the-art methods and summarize five challenges. We are trying to answer the three questions above, and we hope to provoke deeper thought and spark new ideas for the audience.

Survey Organization. The remainder of this paper is organized as follows. In next several sections, we discuss the main challenges in CRSs. Specifically, in Section 2, we illustrate how CRSs can elicit user preferences by asking informative questions. In Section 3, we describe the strategies in CRSs to interact with users in a multi-turn conversation. In Section 4, we point out the problems and provide solutions in dialogue understanding and generation for CRSs. In Section 5, we discuss how CRSs can balance the exploration-exploitation trade-off. In Section 6, we explore metrics and present techniques for evaluating CRSs. In Section 7, we envision some promising future research directions. And in Section 8, we conclude this survey.

Table 1

Five primary challenges in CRSs and part of the classic methods that contribute to these challenges.

Primary Challenges in CRSs	Contributions of Existing Studies	Classic Publications
Question-based User Preference Elicitation	Asking about items	(Zhao et al., 2013; Christakopoulou et al., 2016; Yu et al., 2019b; Zou et al., 2020b; Mangili et al., 2020; Vendrov et al., 2020; LoeppTim Hussein and Ziegler, 2014)
	Asking about attributes	(Mangili et al., 2020; YangScott et al., 2021; Wu et al., 2019a; Christakopoulou et al., 2018; Zhang et al., 2018; Sun and Zhang, 2018; Lei et al., 2020a, 2020b; Zhou et al., 2020a)
Multi-turn Conversational Strategies	Explicit strategies	(Sun and Zhang, 2018; Zhang et al., 2018; Lei et al., 2020a; Xu et al., 2021)
	Leading diverse topics	(Liu et al., 2020ab; Zhou et al., 2020c)
Language Understanding and Generation	End-to-end dialogue systems	(Li et al., 2018; Chen et al., 2019bb; Zhou et al., 2020a; Xu et al., 2020; Moon et al., 2019)
Exploration and Exploitation Trade-offs	Leveraging multi-armed bandits	(Christakopoulou et al., 2016; Zhang et al., 2020c; Li et al., 2021b; Yu et al., 2019b)
Evaluation and User Simulation	Evaluation	(Gilotte et al., 2018; Huang et al., 2020)
	User simulation	(Zhang and Balog, 2020; Sun et al., 2021)

2. Question-based user preference elicitation

A user looking for items with specific attributes may get assess to them by actively searching. For instance, a user may search “iphone12 red 256gb”, where the key phrases “red” and “256gb” are the attributes of the item iPhone12. In this scenario, users construct a query themselves, and the performance relies on both the search engine and the user’s expertise in constructing queries. Even though there are efforts on helping users complete queries by suggesting possible options based on what they entered (Ma et al., 2008; Bar-Yossef and Kraus, 2011; Dehghani et al., 2017; Cai and de Rijke, 2016), users still need to figure out appropriate query candidates. Besides, searching in this way requires users to be familiar with each item they want, which is not true in practice. Recommender systems introduce users to the potential items that they may like. However, traditional recommender systems can only utilize the static historical records as the input, which results in the two main limitations mentioned in mysecintro.

Fortunately, CRSs can bridge the gap between the search engine and recommender system. Empowered by real-time interactions, CRSs can proactively consult users by asking questions. And with the feedback returned by users, CRSs can directly comprehend users’ needs and attitudes towards certain attributes, hence making proper recommendations. Even if users are not satisfied with the recommended items, a CRS has the opportunity to adjust its recommendations in the interaction process.

Question-driven methods focus on the problem of *what to ask* in conversations. Generally, there are two kinds of methods: (1) asking about items (Zhao et al., 2013; Christakopoulou et al., 2016; Sepliarskaia et al., 2018), or (2) asking about attributes/topics/categories of items (Lei et al., 2020a, 2020b).

2.1. Asking about items

Early studies directly ask users for opinions about an item itself (Zhao et al., 2013; Wang et al., 2018; Christakopoulou et al., 2016; Zou et al., 2020b; Vendrov et al., 2020). Unlike traditional recommender systems which need to estimate user preferences in advance, CRSs can construct and modify the user profile during the interaction process.

In traditional recommender system models, the recommended items are produced in a relatively stable way from all candidates. In the CRS scenario, the recommended items should be updated after the system receives feedback from a user and it could be a complete change in order to adapt to the user’s real-time preferences. Hence, instead of merely updating parameters of models online, some explicit rules or mechanisms are required. We introduce three methods that can elicit users’ attitudes towards items and can quickly adjust recommendations. Most

of these methods did not use natural language in their user interface, but it can easily integrate an natural language-based interface to make a CRS.

Choice-based Methods. The main idea of choice-based preference elicitation is to recurrently let users choose their preferred items or item sets from the current given options. The common strategies include (1) choosing an item from two given options (Sepliarskaia et al., 2018), (2) selecting an item from a list of given items (Jiang and QiHe, 2014; Gras and Willemsen, 2015; Saavedra et al., 2016), and (3) choosing a set of items from two given lists (LoeppTim Hussein and Ziegler, 2014).

After the user chooses preferred items, the methods change the recommendations according to the user’s choice. For example, Loepp et al. (LoeppTim Hussein and Ziegler, 2014) use the matrix factorization (MF) model (Bell et al., 2007) to initialize the embedding vectors of users and items, then select two sets of items from the item embedding space as candidate sets and let a user choose one of the two sets. It is important to ensure that the two candidate sets are as different or distinguishable as possible. To achieve this, the authors adopt a factor-wise MF algorithm (Bell et al., 2007), which factorizes the user-item interaction matrix and obtains the embedding vectors one by one in decreasing order of explained variance. Hence, the factors, i.e., different dimensions of embedding vectors, are ordered by distinctiveness. Then, the authors iteratively select two item sets with only a single factor value varying. For example, if two factors represent the degree of *Humor* and *Action* of movies, respectively, then the two candidate sets are one set of movies with a high degree of *Humor* and another with a low degree of *Humor*, while the degree of *Action* of the two sets is fixed to the average level. When a user chooses one item set, the user’s preference embedding vector is set to the average of the embedding vectors of the chosen items. The choice becomes harder as the interaction process continues. Users can choose to ignore the question, which means the users cannot tell the difference between the two item sets or they do not care about it. Carenini et al. (2003) further explore other strategies to select query items, e.g., selecting the most popular or the most diverse items in terms of users’ history.

Bayesian Preference Elicitation. In addition, there are studies based on a probabilistic view of preference elicitation, which has been researched for a long time (Chajewska et al., 1998; Boutilier, 2002; Vendrov et al., 2020). Basically, there is a utility function or a score function $u(\mathbf{x}_j, \mathbf{u}_i)$ representing user i ’s preference for item j . Usually, it can be written as a linear function as

$$u(\mathbf{x}_j, \mathbf{u}_i) = \mathbf{x}_j^T \mathbf{u}_i. \quad (1)$$

In a Bayesian setting, user i ’s preference is modeled by a probabilistic distribution instead of a deterministic vector, which means that the vector \mathbf{u}_i is sampled from a prior user belief $P(\mathcal{U}^{(i)})$. Therefore, the utility

of an item j for a user i is computed as the expectation:

$$\mathbb{E}[u(\mathbf{x}_j, \mathbf{u}_i)] = \int_{\mathbf{u}_i \sim \mathcal{U}^{(i)}} P(\mathbf{u}_i) u(\mathbf{x}_j, \mathbf{u}_i) d\mathbf{u}_i. \quad (2)$$

The item with the maximum expected utility for user i is considered as the recommendation items:

$$\arg \max_j \mathbb{E}[u(\mathbf{x}_j, \mathbf{u}_i)]. \quad (3)$$

Based on the utility function, the system can select some items to query. And the user belief distribution can be updated based on users' feedback. Specifically, given a user response r_i to the question q , the posterior user belief $P(\mathbf{u}_i|q, r_i)$ can be written as:

$$P(\mathbf{u}_i|q, r_i) = \frac{P(r_i|q, \mathbf{u}_i)P(\mathbf{u}_i)}{\int_{\mathcal{U}^{(i)}} P(r_i|q, \mathbf{u}_i)P(\mathbf{u}_i) d\mathbf{u}_i}. \quad (4)$$

As for the query strategy, i.e., selecting which items to ask, there are different criteria. For example, [Boutilier \(2002\)](#) propose a partially observed Markov decision process (POMDP) framework as the sequential query strategy. And [Vendrov et al. \(2020\)](#) and [Guo and Sanner \(GuoScott, 2010\)](#) use the expected value of information (EVOI) paradigm as a relatively myopic strategy to select items to query. Furthermore, the query type can be classified into two different types:

(1) a pairwise comparison query, in which the users are required to choose what they prefer more between two items or two item sets ([Christakopoulou et al., 2016; GuoScott, 2010; Sepliarskaia et al., 2018](#)); or (2) a slate query, where users need to choose from multiple given options ([Vendrov et al., 2020](#)).

Interactive Recommendation. Interactive recommendation models are mainly based on reinforcement learning. Some researchers adopt a multi-armed bandit (MAB) algorithm ([Zhao et al., 2013; Christakopoulou et al., 2016; Wang et al., 2018](#)). The advantage is two-fold. First, MAB algorithms are efficient and naturally support conversational scenarios. Second, MAB algorithms can exploit the items that users liked before and explore items that users may like but never tried before. There are also researchers formulate the interactive recommendation as a meta learning problem which can quickly adapt to new tasks ([Zou et al., 2020b; LeeJinbae et al., 2019](#)). A task here is to make recommendations based on several conversation histories. Meta learning methods and MAB-based methods have the capability of balancing exploration and exploitation. We will describe it later in Section 5.

Recently, researchers incorporate deep reinforcement learning (DRL) models into interactive recommender systems ([Zhao et al., 2018; Chen et al., 2019ba; Xian et al., 2019; Zheng et al., 2018; HuQing et al., 2018; Zou et al., 2019; Chen et al., 2019aa; Ie et al., 2019; Liao et al., 2018; Pecune et al., 2019; Zhou et al., 2020b; Zou et al., 2020a; Wang et al., 2020c](#)). Unlike MAB-based methods which usually assume the user preference is unchanged during the interaction, DRL-based methods can model a dynamic preference and long-term utility. For example, [Mahmood and Ricci \(2007\)](#) introduce a model-based techniques and use the policy iteration algorithm ([Sutton and Barto, 2018](#)) to acquire an adaptive strategy. Model-free frameworks such as deep Q-network (DQN) ([Zhao et al., 2018; Zheng et al., 2018; Zou et al., 2019; Zhou et al., 2020b](#)) and deep deterministic policy gradient (DDPG) ([HuQing et al., 2018](#)) are used in interactive recommendation scenarios. Most reinforcement learning (RL)-based methods often suffer from low efficiency issues and cannot handle cold-start users. [Zhou et al. \(2020b\)](#) propose to integrate a knowledge graph into the interactive recommendation to solve these problems.

For more works that leverage RL in interactive recommender systems, we refer the interested readers to the comprehensive survey conducted by [Afsar et al. \(2021\)](#).

However, directly requiring items is inefficient for building the user profile because the candidate item set is large. In real-world CRS applications, users will get bored as the number of conversation turns

increases. It is more practical to ask attribute-centric questions, i.e., to ask users whether they like an attribute (or topic/category in some works), and then make recommendations based on these attributes ([Zhang et al., 2018; Lei et al., 2020a](#)). Therefore, the estimation and utilization of a user's preferences towards attributes become a key research issue.

2.2. Asking about attributes

Asking about attributes is more efficient because whether users like or dislike an attribute can significantly reduce the recommendation candidates. The challenge is to determine a sequence of attributes to ask so as to minimize the uncertainty of current user needs ([Mirzadeh et al., 2005; Thompson et al., 2004](#)). The aforementioned critiquing-based methods fall into this category. Besides, there are other kinds of methods, we introduce some mainstream branches as below.

2.2.1. Fitting patterns from historical interaction

A conversation can be deemed as a sequence of entities including consumed items and mentioned attributes, and the objective is to learn to predict the next attribute to ask or the next item to recommend. Therefore, the sequential neural network such as the gated recurrent unit (GRU) model ([ChoBart van Merriënboer et al., 2014](#)) and the long short term memory (LSTM) model ([HochreiterJürgen Schmidhuber, 1997](#)) can be naturally adopted in this setting, due to its ability to capture long and short term dependency in user behavioral patterns.

An exemplar work is the question & recommendation (Q&R) model proposed by [Christakopoulou et al. \(2018\)](#), where the interaction between the system and a user is implemented as a selection system. In each turn, the system asks the user to choose one or more distinct topics (e.g., NBA, Comics, or Cooking) from the given list, and then recommends items in these topics to the user. It contains a trigger module to decide whether to ask a question about attributes or to make a recommendation. The triggering mechanism can be as simple as a random mechanism or can be more sophisticated, i.e., using criteria capturing the user's state, or even be user-initiated. At the t -th time step, the next topic q that user click can be predicted based on the user's watching history e_1, \dots, e_T as: $P(q|e_1, \dots, e_T)$. After user clicking a topic q , the model can recommend an item r based on the conditional probability written as: $P(r|e_1, \dots, e_T, q)$. Both of the two conditional probabilities are implemented as the GRU architecture ([ChoBart van Merriënboer et al., 2014](#)). This algorithm is deployed on YouTube, for obtaining preferences from cold-start users.

[Zhang et al. \(2018\)](#) propose a "System Ask User Response" (SAUR) paradigm. For each item, they utilize the rich review information and convert a sentence containing an aspect-value pair to a latent vector via the GRU model. Then they adopt a memory module with attention mechanism ([SukhbaatarArthur Szlam et al., 2015; Kumar et al., 2016; Miller et al., 2016](#)) to perform both the next question generation task (determining which attribute to ask) and the next item recommendation task. Again, they also develop a heuristic trigger to decide whether it is the time to display the top- n recommended items to users or to keep asking questions about attributes. One limitation of the work is that the authors assume all information in reviews can support the purchasing behavior, however it is not true as users may complain certain aspects of the purchased items, e.g., a user may write "64 Gigabytes is not enough". Using information without discrimination will mislead the model and deteriorate the performance.

The utterances produced by the system, i.e., the questions, are constructed with predefined language patterns or templates, meaning that what the system needs to pay attention to are only the aspect and the value. This is a common setting in state-of-the-art CRS studies because the core task here is recommendation instead of language generation ([Christakopoulou et al., 2018; Lei et al., 2020a, 2020b](#)).

Note that these kinds of methods have a common disadvantage: learning from historical user behaviors cannot aid understanding the

logic behind the interaction. As interactive systems, these models do not consider how to react to feedback when users reject the recommendation, i.e., they just try to fit the preferences in historical interaction and do not consider an explicit strategy to deal with different feedback.

2.2.2. Reducing uncertainty

Unlike sequential neural network-based methods that do not have an explicit strategy to handle all kinds of user feedback, some studies try to build a straightforward logic to narrow down item candidates.

Critiquing-based Methods. The aforementioned critiquing model is typically equipped with a heuristic tactic to elicit user preference on attributes (Chen and Pu, 2012; Wu et al., 2019a; Luo et al., 2020b; LuoScott et al., 2020). In traditional critiquing models, where the critique on an attribute value (e.g., “not red” for color or “less expensive” for price) is used for reconstructing the candidate set by removing the items with unsatisfied attributes (Chen and Pu, 2012; McCarthy et al., 2004; Smyth et al., 2004; Viappiani et al., 2007; Burke et al., 1997; Smyth and McGinty, 2003). The neural vector-based methods take the criticism into the latent vector, which is responsible for generating both the recommended items and the explained attributes. For example, Wu et al. (2019a) propose an explainable neural collaborative filtering (CE-NCF) model for critiquing. They use the NCF model (He et al., 2017) to encode the preference of a user i for an item j as a latent vector \hat{z}_{ij} , then \hat{z}_{ij} is used for producing the rating score \hat{r}_{ij} as well as the explained attribute vector \hat{s}_{ij} . The attributes are composed of a set of key-phrases such as “golden, copper, orange, black, yellow,” and each dimension of \hat{s}_{ij} corresponds to a certain attribute. When a user dislikes an attribute and critique it in real-time feedback, the system updates the explained attribute vector \hat{s}_{ij} by setting the corresponding dimension to zero. Then the updated vector \tilde{s}_{ij} is used to update the latent vector \hat{z}_{ij} to be \tilde{z}_{ij} . Consequently, the recommendation score is updated to be \tilde{r}_{ij} . Following this setting, Luo et al. (2020b) change the base NCF model (He et al., 2017) to be a variational autoencoder (VAE) model, and this generative model can help the critiquing system have better computational efficiency, improved stability, and faster convergence.

Reinforcement Learning-driven Methods. Reinforcement learning is also used in CRSs to select the appropriate attributes to ask (Sun and Zhang, 2018; Lei et al., 2020a, 2020b). Empowered by a deep policy network, the system not only selects the attributes but also determine a controlling strategy on when to change the topic of the current conversation; we will elaborate this in Section 3.1 where we describe how reinforcement learning helps the system form a multi-turn conversational strategy.

Graph-constrained Candidates. Graph is a prevalent structure to represent relationship of different entities. It is natural to utilize graphs to sift items given a set of attributes. For example, Lei et al. (2020b) propose an interactive path reasoning algorithm on a heterogeneous graph on which users, items, and attributes are represented as nodes and an edge connected two nodes represented a relationship between two nodes, e.g., a user purchased an item, or an item has a certain value for an attribute. With the help of the graph, a conversation can be converted to a path on the graph, as illustrated in Fig. 4. The authors compare the uncertainty of preference for attributes and choose the attributes with the maximum uncertainty to ask. Here, the preference for a certain attribute is modeled by the average preference for items that have this attribute. Hence, the searching space and overhead of the algorithm can be significantly reduced by utilizing the graph information. There are other studies that apply graph neural networks (GNNs) to learn a powerful representation of both items and attributes, so the semantic information in the learned embedding vectors can help end-to-end CRS models generate appropriate recommendations. For example, the GCN model and its variants (Kipf and Welling, 2017; Schlichtkrull et al., 2018) are adopted on the knowledge graph in recent CRS models (Chen et al., 2019b; Zhou et al., 2020a; Xu et al., 2020; Liao et al., 2020).

Other Methods. There are other attempts to make recommendations

based on user feedback on attributes. For example, Zou et al. (Zou et al., 2020) proposed a question-driven recommender system based on an extended matrix factorization model, which merely considers the user rating data, to combine real-time feedback from users.

The basic assumption is that if a user likes an item, then he/she will like the attributes of this item. Thereby, in each turn, the system will select the attribute that carries the maximum amount of uncertainty to ask. In other words, if an attribute is known to be shared by most items that a user likes, then it does not need to ask about this attribute. Similarly, there is no need to ask about the attributes that users dislike. Only if it is not sure whether a user likes an attribute, then asking about this attribute can provide the most amount of information. The parameters in matrices can be updated after users providing feedback. Besides, using ideas similar to aforementioned models based on asking items, MAB-based models (Zhang et al., 2020c; Li et al., 2021b) and Bayesian approaches (Mangili et al., 2020) are also developed in attribute-asking CRSs.

2.3. Section summary

We list the common CRS models in Table 2, where the models are characterized by different dimensions, which are the asking entity (item or attribute), the asking mechanism, the type of user feedback, and the multi-turn strategy that we will describe in the next section.

In most interactive recommendations (Zou et al., 2020a; Wang et al., 2020c; ZhangTong et al., 2019b; Ding et al., 2020) and critiquing methods (Chen and Pu, 2012; Wu et al., 2019a; Luo et al., 2020b; LuoScott et al., 2020), the system keeps asking questions, and each question is followed by a recommendation. This process will only terminate when users quit with either being satisfied or impatient. The setting is unnatural and will likely hurt the user experience during the interaction process. Asking too many questions may let the interaction become an interrogation. Moreover, during the early stages of interaction, when the system has not confidently modeled the user preferences yet, recommendations with low confidence should not be exposed to the user (Schnabel et al., 2018). In other words, there should be a multi-turn conversational strategy to control how to switch between asking and recommending, and this strategy should change dynamically in the interaction process.

3. Multi-turn conversational strategies for CRSs

Question-driven methods focus on the problem of “*What to ask*”, and the multi-turn conversational strategies discussed in this section focus on “*When to ask*” or a broader perspective, “*How to maintain the conversation*”. A good strategy cannot only make the recommendation at the proper time (with high confidence) and adapt flexibly to users’ feedback, but also maintain the conversation topics and adapt to different scenarios to make users feel comfortable in the interaction.

3.1. Conversation strategies for determining when to ask and recommend

Most CRS models do not carefully consider a strategy to determine whether to continue interrogating users by asking questions or to make a recommendation. However, a good strategy is essential in the interaction process so as to improve the user experience. The strategy can be a rule-based policy, i.e., making recommendations every k turns of asking questions (Zhang et al., 2020c), or a random policy (Christakopoulou et al., 2018), or a model-based policy (Christakopoulou et al., 2018).

In the SAUR model (Zhang et al., 2018), a trigger is set to activate the recommendation module when the confidence is high. The trigger is simply implemented as a sigmoid function on the score of the most probable item, i.e., if the score of the candidate item is high enough, then the recommendation step is triggered, else the system will keep asking questions.

Though straightforward and easy to control, these strategies cannot

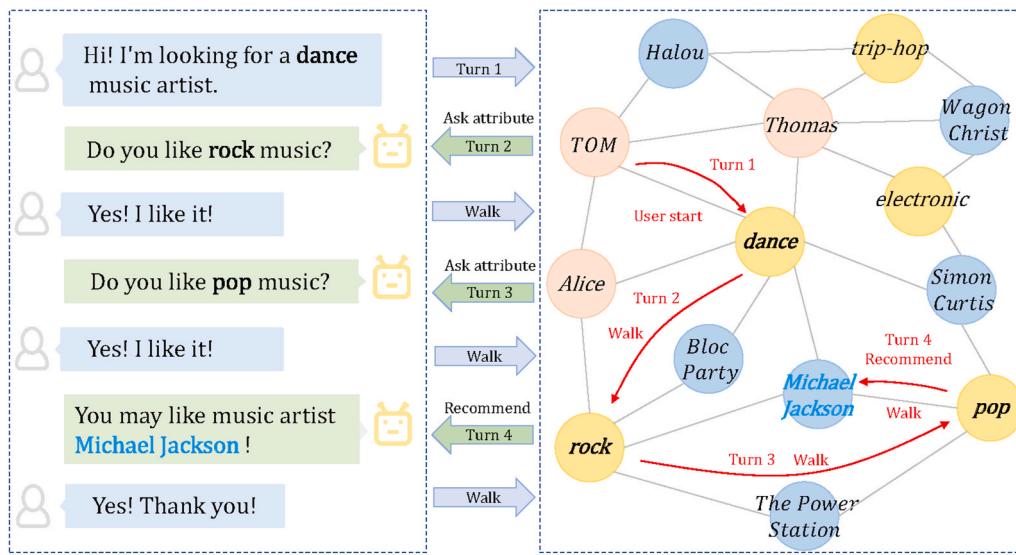


Fig. 4. An illustration of interactive path reasoning in the CPR model. Credits: Lei et al. (Lei et al., 2020b).

Table 2

Characteristics of common CRS models in different dimensions. The strategy indicates whether the work considers an explicit strategy to control multi-turn conversations, e.g., whether to ask or recommend in the current turn.

Asking	Asking Mechanism	Basic Model	Type of User Feedback	Strategy	Publications
Items	Exploitation & Exploration	Multi-armed bandit	Rating on the given item(s)	No	(Zhao et al., 2013; Christakopoulou et al., 2016; Zhou et al., 2020e; WangSteven et al., 2017; Yu et al., 2019b)
	Exploitation & Exploration	Meta learning	Rating on the given item(s)	No	(Zou et al., 2020b; LeeJinbae et al., 2019)
	Maximal posterior user belief	Bayesian methods	Rating on the given item(s)	No	Vendrov et al. (2020)
	Reducing uncertainty	Choice-based methods	Choosing an item or a set of items	No	(LoeppTim Hussein and Ziegler, 2014; Jiang and QiHe, 2014; Graus and Willemsen, 2015; Saavedra et al., 2016; Rana and Bridge, 2020)
Attributes	Exploitation & Exploration	Multi-armed bandit	Rating on the given attribute(s)	Yes	(Zhang et al., 2020c; Li et al., 2021b)
	Reducing uncertainty	Bayesian approach	Providing preferred attribute values	No	(Mangili et al., 2020; YangScott et al., 2021)
		Critiquing-based methods	Critiquing one/multiple attributes	No	(McCarthy et al., 2004; Smyth et al., 2004; Viappiani et al., 2007; Burke et al., 1997; Smyth and McGinty, 2003) (Pu and Faltings, 2004; Chen and Pu, 2012; Wu et al., 2019a; Luo et al., 2020b; LuoScott et al., 2020)
		Matrix factorization	Answering Yes/No for an attributes	No	Zou et al. (2020)
Fitting historical patterns	Sequential neural network	Providing preferred attribute values	Yes		(Christakopoulou et al., 2018; Zhang et al., 2018)
		Providing an utterance	No		(Li et al., 2018; Chen et al., 2019bb)
Maximal reward	Reinforcement learning	Answering Yes/No for an attributes	Yes		(Lei et al., 2020a, 2020b)
		Providing an utterance	Yes		(Kang et al., 2019; Sun and Zhang, 2018; Tsumita and Takagi, 2019)
			No		Ren et al. (2020)
Exploring graph-constrained candidates	Graph reasoning	Answering Yes/No for an attributes	Yes		Lei et al. (2020b)
		Providing an utterance	Yes		(Chen et al., 2019bb; Liu et al., 2020ab)
			No		(Zhou et al., 2020a; Liao et al., 2020)
		Providing preferred attribute values	Yes		Xu et al. (2020)
			No		Moon et al. (2019)

capture rich semantic information, e.g., what topics are talking about now or how deep the topics have been explored. This information can directly affect the conversation topic. Thereby, a sophisticated strategy

is necessary. Recently, reinforcement learning (RL) has been adopted by many interactive recommendation models for its potential of modeling the complex environment (Zhao et al., 2018; Chen et al., 2019ba; Xian

et al., 2019; Zheng et al., 2018; Zou et al., 2019; Chen et al., 2019aa; He et al., 2019; Liao et al., 2018; Pecune et al., 2019; ZhangTong et al., 2019b; Zhou et al., 2020b). Therefore, it is natural to incorporate RL into the CRS framework (Sun and Zhang, 2018; Lei et al., 2020a, 2020b; Tsumita and Takagi, 2019; Ren et al., 2020; Kang et al., 2019). For instance, Sun and Zhang (2018) propose a model called conversational recommender model (CRM) that uses the architecture of task-oriented dialogue system. In CRM, a belief tracker is used to track the users' input, and it outputs a latent vector representing the current state of the dialogue and the user preferences that have so far been captured. Afterward, the state vector of the belief tracker is input into a deep policy network to decide whether to recommend an item or to keep asking questions. Specifically, there are $l + 1$ actions: l actions for choosing one facet to ask and the last one is to yield a recommendation. The deep policy network uses the policy gradient method to make decisions. Finally, the model gets rewards from the environment, which includes user feedback towards the questions and the reward from the automatic evaluation of recommendation results.

However, the state modeled in CRM is a latent vector capturing the information of facet-values, which is hard to interpretable. In this respect, some studies explore better ways to construct the state of RL to make the multi-turn conversation strategy better adapt to an dynamic environment. For example, Lei et al. (2020a) propose an Estimation-Action-Reflection (EAR) framework, which assumes that the model should only ask questions at the right time. The right time, in their definition, is when (1) the item candidate space is small enough; (2) asking additional questions is determined to be less useful or helpful, from the perspective of either information gain or user patience; and (3) the recommendation engine is confident that the top recommendations will be accepted by the user.

The workflow of the EAR framework is illustrated in Fig. 5, where the system has to decide whether to continue to ask questions about attributes or to make a recommendation based on available information. To determine when to ask a question, they construct the state of the RL model to take into account four factors:

- Entropy information of each attribute among the attributes of the current candidate items. Asking attributes with a large entropy helps to reduce the candidate space, thus benefits finding desired items in fewer turns.
- User preference on each attribute. The attribute with a high predicted preference is likely to receive positive feedback, which also helps to reduce the candidate space.
- Historical user feedback. If the system has asked about a number of attributes for which the user gives approval, it may be a good time to recommend.

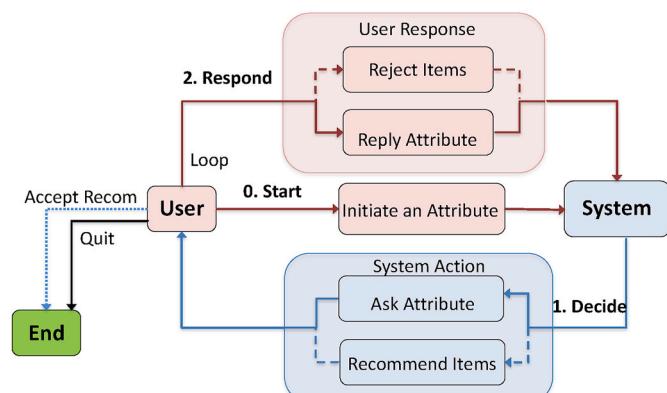


Fig. 5. The estimation-action-reflection workflow. Credits: Lei et al. (Lei et al., 2020a).

- Number of rest candidates. If the candidate list is short enough, the system should turn to recommend to avoid wasting more turns.

Building on these vectors capturing the current state, the RL model learns the proper timing to ask or recommend, which is more intelligent than a fixed heuristic strategy.

During the conversation, the recommendation module takes the items in the previous list of recommendations that are not chosen by users as the negative samples. However, Lei et al. (2020a) mention that this setting deteriorates the performance of the recommendation results. The reason, as they analyze it, is that rejecting the produced attribute does not mean that the user dislikes it: maybe the user does like it but overlooks it or just wants to try other new things.

Furthermore, Lei et al. (2020b) extend the EAR model by proposing the CPR model. By integrating the knowledge graph consisted of users, items, and attributes, they model conversational recommendation as an interactive path reasoning problem on the graph. A toy example of the generated conversation of the CPR model is shown in Fig. 4. Unlike the EAR model where the attributes to be asked are selected irregular and unpredictable from all attribute candidates, CPR chooses attributes to be asked and items to be recommended strictly following the paths on the knowledge graph, which renders interpretable results.

In terms of the timing to ask or recommend, CRP makes an important improvement: the action space of the RL policy is only two — asking an attribute or making item recommendations. This largely reduces the difficulty of learning the RL policy. The CPR model is much more efficient than the EAR model due to the fact that the searching space of attributes in CPR is constrained by the graph. The integration of knowledge improves the multi-turn conversational reasoning ability.

3.2. Conversation strategies from a broader perspective

Although learning from the query-answering interactions can enable the system to understand and respond to human query directly, the system still lacks intelligence. One reason is that most CRS models assume that users always bear in mind what they want, and the task is to obtain the preference through asking questions. However, users who resort to recommendation might not have a clear idea about what they really want. Just like a human asks a friend for suggestions on restaurants. Before that, he may not have a certain target in mind, and his decision can be affected by his friend's opinions. Therefore, CRSs should not only ask clarification questions and interrogate users, but also take responsibility for leading the topics and affecting users' mind. Towards this objective, some studies try to enrich CRSs certain personalities or endow CRSs the ability to lead the conversation, which can make the dialogues more attractive and more engaging. These efforts can also be found in the field of proactive conversation (Mo et al., 2018; Wu et al., 2019; Balaraman and Magnini, 2020).

3.2.1. Multi-topic learning in conversations

Borrowing the idea from the proactive conversation, Liu et al. (Liu et al., 2020ab) present a new task which places conversational recommendation in the context of multi-type dialogues. In their model, the system can proactively and naturally lead a conversation from a non-recommendation dialogue (e.g., question answering or chitchat) to a recommendation dialogue, taking into account the user's interests and feedback. And during the interaction, the system can learn to flexibly switch between multiple goals. To address this task, they propose a multi-goal driven conversation generation (MGCG) framework, which consists of a goal planning module and a goal-guided responding module. The goal-planning module can conduct dialogue management to control the dialogue flow, which takes recommendation as the main goal and complete the natural topic transitions as the short-term goals. Specifically, given a user's historical utterances as context X and the last goal g_{t-1} , the module estimates the probability of changing the goal g_t of the current task as $P_{GC}(g_t \neq g_{t-1} | X, g_{t-1})$. The goal g_t of the current task is

changed when the probability $P_{GC} > 0.5$ and remains to be g_{t-1} if $P_{GC} \leq 0.5$. Based on the current goal, the framework can produce responses from an end-to-end neural network.

Learning a multi-type conversational model requires a dataset that supports multi-type dialogues. Therefore, Liu et al. (Liu et al., 2020ab) create a dataset, denoted as DuRecDial, with various types of interaction. In DuRecDial, two human workers are asked to conduct the conversation based on a given profile, which contains the information of age, gender, occupation, preferred domains, and entities. The workers must produce utterances that are consistent with their given profiles, and they are encouraged to produce utterances with diverse goals, e.g., question answering, chitchat, or recommendation. Then these dialogue data are labeled with goals and goal descriptions by templates and human annotation.

Further, Zhou et al. (2020c) release a topic-guided conversational recommendation dataset. They collect the review data from Douban Movie², a movie review website, to construct the recommended movies, topic threads, user profiles, and utterances. And they associate each movie with the concepts in ConceptNet (Speer et al., 2017), a commonsense knowledge graph, for providing rich topic candidates. Then they use rules to generate multi-turn conversations with diverse topics based on the user profile and topic candidates. Based on the proposed dataset, a new task of topic-guided conversational recommendation is defined as follows: given the user profile P_u , user interaction sequence I_u , historical utterances s_1, \dots, s_{k-1} , and corresponding topic sequence $\{t_1, \dots, t_{k-1}\}$, the system should: (1) predict the next topic t_k , or (2) recommend the movie i_k , and finally (3) produce a proper response s_k about the topic and with persuasive reasons.

3.2.2. Special ability: suggesting, negotiating, and persuading

There are miscellaneous tasks beyond the preference elicitation and recommendation for an intelligent interactive system, which require the CRS to possess different abilities to react in different scenarios. This is a high-level and abstract requirement. A lot of effort have put into helping the machine improve the topic's guiding ability. For instance, in conversational search (Voskarides et al., 2020; ter Hoeve et al., 2020; Ren et al., 2020b; Vakulenko et al., 2020b; Vakulenko et al., 2021; Ren et al., 2021), where traditional work has mainly attempted to better understand a user's information needs by resolving ambiguity, the conversational search engine aims to lead the conversation with questions that a user may want to ask in the next step. For example, if a user queried “Nissan GTR Price,” then the system can provide question suggestions include those that help the user complete a task (“How much does it cost to lease a Nissan GT-R?”), weigh options (“What are the pros and cons of the Nissan GT-R?”), explore an interesting related topic (“Is the Nissan GT-R the ultimate streetcar?”), or learn more details (“How much does 2020 Nissan GTR cost?”) (Rosset et al., 2020). These question suggestions can lead the user to an immersive search experience with diverse and fruitful future outcomes.

In addition, Lewis et al. (2017) propose a system that is capable of engaging in the negotiations with users. They define the problem as an allocation problem: there are some items that need to be allocated to two people, where each item has a different value to a different person and people do not know the value of others. Hence, the two people have to converse and negotiate with each other to reach an agreement about the division of these items. Instead of optimizing relevance-based likelihood, the model should pursue a maximal profit for both parties. The authors use RL to tackle this problem. And they interleave RL updates with supervised updates to avoid that the models diverges from human language.

Wang et al. (2019) develop a model that tries to persuade users to take certain actions, which is very promising for conversational recommendation. They train the model, according to conversational

contexts, to learn and predict the 10 persuasion strategies (e.g., logical appeal or emotion appeal) used in the corpus. And they analyze which strategies are better conditioned on the background (personality, morality, value systems, willingness) of the user being persuaded.

Though some of these efforts are applied to specific application scenarios in dialogue systems, these techniques can be adopted in the multi-turn strategy in CRSs and thus push the development of CRSs.

3.3. Section summary

The multi-turn conversation strategies of CRSs discussed in this section are summarized in Table 3. The main focus of the conversation strategy is to determine when to elicit user preference by asking questions and when to make recommendations. As a recommendation should only be made when the system is confident, an adaptive strategy can be more promising compared to a static one. Besides this core function, we introduce some strategies from a broader perspective. These strategies can extend the capability of CRSs by means of leading multi-topic conversations (Liu et al., 2020ab; Zhou et al., 2020c) or showing special ability such as suggesting (Rosset et al., 2020), negotiating (Lewis et al., 2017), and persuading (Wang et al., 2019).

4. Dialogue understanding and generation in CRSs

An important direction of CRSs is to converse with humans in natural languages, thus understanding human intentions and generating human-understandable responses are critical. However, most CRSs only extract key information from processed structural data and present the result via rule-based template responses (Zhang et al., 2018; Zou et al., 2020; Lei et al., 2020a, 2020b). This not only requires lots of labor to construct the rule or template but also make the result rely on the pre-processing. It also hurt user experience as the constrained interaction is unnatural in real-world applications. Recently, we have witnessed the development of end-to-end learning frameworks in dialogue systems, which have been studying for years to automatically handle the semantic information in raw natural language (Gao et al., 2019a; Lei et al., 2018; Jin et al., 2018). We will introduce these natural language processing (NLP) technologies in dialogue systems and describe how they help CRSs understand user intention and sentiment and generate meaningful responses.

4.1. Dialogue understanding

Understanding users' intention is the key requirement for the user interface of a CRS, as downstream tasks, e.g., recommendation, rely heavily on this information. However, most CRSs pay attention to the core recommendation logic and the multi-turn strategy, while they circumvent extracting user intention from raw utterances and requires the preprocessed input such as rating scores (Zhao et al., 2013; Christakopoulou et al., 2016; Zou et al., 2020b; LeeJinbae et al., 2019), YES/NO answers (Zou et al., 2020; Lei et al., 2020a, 2020b), or another type of value or orientation (Christakopoulou et al., 2018; Zhang et al., 2018) towards the queried items or attributes. This is unnatural in real-life human conversation and imposes constraints on user expression. Thereby, it is necessary to develop methods to extract semantic information in users' raw language input, either in an explicit or implicit way.

We introduce how dialogue systems use NLP technologies to address this problem and give the examples of CRSs that use these technology to understand user intention.

4.1.1. Slot filling

A common way used in dialogue systems to extract useful information is to predefine some aspects of interest and use a model to fill out the values of these aspects from users' input, a.k.a, slot filling (Deng et al., 2012; Deoras and Sarikaya, 2013; Yao et al., 2013, 2014; Mesnil et al.,

² <https://movie.douban.com/>.

Table 3

The commonly used multi-turn strategies in CRSs.

Main Mechanism	Asking Method	When to ask and recommend	Determining X and Y	Publications
Asking questions	Explicit	Asking 1 turn; recommending 1 turn	Fixed	(Christakopoulou et al., 2018; Yu et al., 2019b)
		Asking X turn(s); recommending 1 turn	Fixed	Zou et al. (2020)
			Adaptive	Sun and Zhang (2018)
	Implicit	Asking X turn(s); recommending Y turn(s)	Adaptive	(Zhang et al., 2018; Lei et al., 2020a, 2020b; Li et al., 2021b; Xu et al., 2021)
Leading diverse topics or explore special abilities		Contained in natural language	Adaptive	(Li et al., 2018; Chen et al., 2019bb; Zhou et al., 2020a; Zhou et al., 2020c)
				(Liu et al., 2020ab; Zhou et al., 2020c; Rosset et al., 2020; Lewis et al., 2017; Wang et al., 2019)

2013; Pecune et al., 2020). Sun and Zhang (2018) first consider extracting the semantic information from the raw dialogue in CRSs. They propose a belief tracker to capture the facet-value pairs, e.g., (color, red), from user utterances. Specifically, given a user utterance e_t at time step t , the input to the belief tracker is the n-gram vector \mathbf{z}_t , which is written as $\mathbf{z}_t = \text{n-gram}(e_t)$, where the dimension of \mathbf{z}_t is the corpus size. This means that only the positions corresponding to the words in utterance e_t are set to 1, other positions will be set to 0. Suppose there are K types of facet-value pairs, for a given facet $m \in \{1, 2, \dots, K\}$, the user's sequential utterances $\mathbf{z}_1, \mathbf{z}_2, \dots, \mathbf{z}_t$ are encoded by a LSTM model (HochreiterJürgen Schmidhuber, 1997) to learn the latent vector f_m for this facet m . The size of vector f_m is set to the number of values, e.g., the number of available colors. The vector f_m capturing the facet-value information will be used in the recommendation module and policy network later. Besides, Ren et al. (2020), Tsumita and Takagi (2019) also employ recurrent neural networks (RNN)-based methods to extract the facet-value information as input for in downstream tasks in their CRSs.

However, explicitly modeling semantic information as aspect-value pairs can be a limitation in some scenarios where it is difficult and also unnecessary to do that. Besides, aspect-value pairs cannot precisely express information such as user intent or sentiment. Therefore, some recent CRSs use end-to-end neural frameworks to implicit learning the representation of users' intentions and sentiment.

4.1.2. Intentions and sentiment learning

Neural networks are famous for extracting features automatically, so it can be used to extract users' intentions and sentiment in CRSs. An classic example in CRSs is the end-to-end framework that proposed by Li et al. (2018), which takes the user's raw utterances as input and directly produces the responses in the interaction. They collect the REDIAL dataset³ through the crowdsourcing platform Amazon Mechanical Turk (AMT)⁴. They pair up AMT workers and give each of them a role. The movie seeker has to explain what kind of movie he/she likes, and asks for movie suggestions. The recommender tries to understand the seeker's movie tastes and recommends movies. All exchanges of information and recommendations are made using natural language; every movie mention is tagged using the "@" symbol to let the machine know it is a named entity. In this way, the dialogues in the REDIAL data contain the required semantic information that can help the model learn to answer users with recommendations and reasonable explanations. In addition, three questions are asked to provide labels for supervised learning: (1) Whether the movie was mentioned by the seeker, or was a suggestion from the recommender ("suggested" label). (2) Whether the seeker has seen the movie ("seen" label): one of *Have seen it*, *Haven't seen it*, or *Didn't say*. (3) Whether the seeker liked the movie or the suggestion ("liked" label): one of *Liked*, *Didn't like*, *Didn't say*. The three labels are

collected from both the seeker and the recommender.

In this way, although the facet-value constraints are removed, all kinds of information including mentioned items and attributes, user attitude, and user interest are preserved and labeled in the raw utterance. And the CRS model needs to directly learn users' sentiment (or preferences), and it will make recommendations and generate responses based on the learned sentiment. The deep neural network-based model consists of four parts: (1) A hierarchical recurrent encoder implemented as a bidirectional GRU (ChoBart van Merriënboer et al., 2014) that transforms the raw utterances into a latent vector with the key semantic information remained. (2) At each time a movie entity is detected (with the "@" identifier convention), an RNN model is instantiated to classify the seeker's sentiment or opinion regarding that entity. (3) An autoencoder-based recommendation module that takes the sentiment prediction as input and produces an item recommendation. (4) A switching decoder generating the response and deciding whether the name of the recommended item is included in the response. The model generates a complete sentence that might contain a recommended item to answer each user's utterance.

Beside using the RNN-based neural networks, there are some CRSs that adopt the convolutional neural network (CNN) model (Ren et al., 2020; Liu et al., 2020ab), which has been proven to be very effective for modeling the semantics from raw natural language (Kim, 2014). However, deep neural networks are often criticized to be non-transparent and hard to interpretable (Buhrmester et al., 2019). It is not clear how the deep language models can help CRSs in understanding user needs.

In order to answer this question, Penha and Hauff (2020) investigate the bidirectional encoder representations from transformers (BERT) (Devlin et al., 2019), a powerful technology for NLP pre-training developed by Google, to analyze whether its parameters can capture and store semantic information about items such as books, movies, and music for CRSs. The semantic information includes two kinds of knowledge needed for conducting conversational search and recommendation, namely content-based and collaborative-based knowledge. Content-based knowledge is knowledge that requires the model to match the titles of items with their content information, such as textual descriptions and genres. In contrast, collaborative-based knowledge requires the model to match items with similar ones, according to community interactions such as ratings. The authors use the three probes on the BERT model (i.e., tasks to examine a trained model regarding certain properties) to achieve the goal. And the result shows that both collaborative-based and content-based knowledge can be learned and remembered. Therefore, the end-to-end language model has potential as part of CRS models to interact with humans directly in real-world applications with complex contexts.

4.2. Response generation

A natural language-based response of a CRS should at least meet two levels of standards. The lower level standard requires the generated language to be proper and correct; the higher level standard requires the

³ <https://redialdata.github.io/website/>.

⁴ <https://www.mturk.com/>.

response contains meaningful and useful information about recommended results.

4.2.1. Generating proper utterances in natural language

Many CRSs use template-based methods to generate responses in conversations (Sun and Zhang, 2018; Lei et al., 2020a, 2020b). However, template-based methods suffer from producing repetitive and inflexible output, and it require intense manual work. Besides, template-based responses could make users uncomfortable and hurt user experience. Hence, it is important to automate the response generation in CRSs to produce proper and fluent responses. This is also the objective of dialogue systems, so we introduce two veins of technologies for producing responses in dialogue systems:

Retrieval-based Methods. The basic idea is to retrieve the appropriate response from a large collection of response candidate. This problem can be formulated as a matching problem between an input user query and the candidate responses. The most straightforward method is to measure the inner-product of the feature vectors representing a query and a response (Wu and Yan, 2018). A key challenge is to learn a proper feature representation (Wu and Yan, 2018). One strategy is to use neural networks to learn the representation vectors from user query and candidate response, respectively. Then, a matching function is used to combine the two representations and output a matching probability (Hu et al., 2014; TanCicero dos Santos et al., 2016; Qiu and Huang, 2015; Feng et al., 2015; Wang et al., 2016b). An alternative strategy, in contrast, is to combine the representation vectors of query and response first, and then a neural method is used on the combined representation pair to further learn the interaction (Wang and Jiang, 2016; Wan et al., 2016; Pang et al., 2016; Lu and Li, 2013). These two strategies have their own advantages: the former is more efficient and suitable for online serving, while the latter is better at efficacy since the matching information is sufficiently preserved and mined (Wu and Yan, 2018).

Generation-based Methods. Unlike retrieval-based methods, which select existing responses from a database of template response, generation-based methods directly produce a complete sentence from the model. The basic generation model is a recurrent sequence-to-sequence model, which sequentially feeds in each word in the query as input, and then generates the output word one by one (SutskeverOriol VinyalsQuoc, 2014). Compared to retrieval-based methods, generation-based methods have some challenges. First, the generated answer is not guaranteed to be a well-formed natural language utterance (Yan et al., 2016). Second, even though the generated response may be grammatically correct, we can still distinguish a machine-generated utterance from a human-generated utterance, since the machine response lacks basic commonsense (Young et al., 2018; Zhou et al., 2018c; Ren et al., 2020a), personality (Qian et al., 2018; Zheng et al., 2020), emotion (Zhou et al., 2018b), and the ability to perceive user profiles (Pei et al., 2021). Even worse, generation models are prone to produce a safe answer, such as “OK,” “I don’t understand what you are talking about,” which can fit in almost all conversational contexts but would only hurt the user experience (Li et al., 2016a; Qiu et al., 2019). Ke et al. (2018) propose to explicitly control the function of the generated sentence, for example, for the same user query, the system can answer with different tones: The interrogative tone can be used to acquire further information; the imperative tone is used to make requests, directions, instructions or invitations to elicit further interactions; and the declarative tone is commonly used to make statements or explanations. Another problem is how to evaluate the generated response, since there is no standard answer; we will further discuss this in Section 6. Researchers borrow the ideas from dialogue systems and apply the technologies in the user interface of CRSs. For instance, Li et al. (2018) generate responses by a decoder where a GRU model (ChoBart van Merriënboer et al., 2014) decodes the context from the previous component (i.e., predicted sentiment towards items) to predict the next utterance step by step. Liu et al. (Liu et al., 2020ab) adopt the

responding model in the work of Wu et al. (2019) and propose both a retrieval-based model and a generation-based model to produce responses in their CRS.

However, a correct sentence does not mean it can fulfill the task of recommendation; at least the name of the recommended entity should be mentioned in generated sentences. Hence, Li et al. (2018) use a switch to decide whether the next predicted word is a movie name or an ordinal word; Liu et al. (Liu et al., 2020ab) introduce an external memory module for storing all related knowledge, making the models select appropriate knowledge to enable proactive conversations. Besides, there are other efforts to guarantee the generated responses should not only be proper and accurate but also be meaningful and useful.

4.2.2. Incorporating recommendation-oriented information

There is a major limitation CRSs that use the end-to-end frameworks as the user interface: only items mentioned in the training corpus have a chance of being recommended since items that have never been mentioned are not modeled by the end-to-end model. Therefore, the performance of this method is greatly limited by the quality of human recommendations in the training data. To overcome this problem, Chen et al. (Chen et al., 2019bb) propose to incorporate domain knowledge to assist the recommendation engine. The incorporation of a knowledge graph mutually benefits the dialogue interface and the recommendation engine in the CRS. (1) the dialogue interface can help the recommender engine by linking related entities in the knowledge graph; the recommendation model is based on the R-GCN model (Schlichtkrull et al., 2018) to extract information from the knowledge graph; (2) the recommender system can also help the dialogue interface: by mining words with high probability, the dialogue can connect movies with some biased vocabularies, thus it can produce consistent and interpretable responses.

Following this line, Zhou et al. (2020a) point out the remaining problems in the dialogue interface in CRSs. Although Chen et al. (Chen et al., 2019bb) have introduced an item-oriented knowledge graph to enable the system to understand the movie-related concepts, the system still cannot comprehend some words in the raw utterances. For example, “thriller”, “scary”, “good plot”. In essence, the problem originates from the fact that the dialogue component and the recommender component correspond to two different semantic spaces, namely word-level and entity-level semantic spaces. Therefore, Zhou et al. (2020a) incorporate and fuse two special knowledge graphs, i.e., a word-oriented graph (ConceptNet (Speer et al., 2017)), and an item-oriented graph (DBpedia (Bizer et al., 2009)), to enhance understanding semantics in both the components. The representations of the same concepts on the two knowledge graphs are forced to be aligned with each other via the mutual information maximization (MIM) technique (Veličković et al., 2019; Yeh and Chen, 2019). Furthermore, a self-attention-based recommendation model is proposed to learn the user preference and adjust the representation of corresponding entities on the knowledge graph. Then, equipped with these representations containing both semantics and users’ historical preferences, the authors use an encoder-decoder model to extract user intention from the raw utterances and directly generate the responses containing recommended items.

Besides, some researchers try to improve the diversity or explainability of generated responses in CRSs. For example, Liu et al. (Liu et al., 2020ab) propose the multi-topic learning that can handle diverse dialogue types in CRSs. To enhance the interpretability of CRSs, Chen et al. (2020b) design an incremental multi-task learning framework to integrate review comments as side information. Hence, the CRS can simultaneously produce a recommendation as well as a sentence as an explanation, e.g., “I recommend *Mission Impossible*, because it is by far the best of the action series.” Moreover, Luo et al. (2020b) use a VAE-based architecture to learn a latent representation for generating recommendations and fitting user critiquing. Therefore, their model can better understand users’ intentions from users’ raw comments, and thus can generate more interpretable responses. Gao et al. (2020) consider

Table 4

Mechanisms of language understanding and generation in CRSs.

Forms of Input & Output	Publications
Pre-annotated Input & Template-based Output	(Zhao et al., 2013; Zou et al., 2020; Loeppe Tim Hussein and Ziegler, 2014; Zhang et al., 2018; Sun and Zhang, 2018), (Christakopoulou et al., 2016, 2018; Lei et al., 2020a, 2020b; Li et al., 2021b; Fu et al., 2021)
Raw Language Input & Natural Language Generation	(Ren et al., 2020; Li et al., 2018; Chen et al., 2019bb), (Zhou et al., 2020a; Ma et al., 2020; Liu et al., 2020ab)

attributes and review information and rewrite a coherent and meaningful answer from a selected prototype answer, which can address the safe answer problem in the response (Li et al., 2016a; Qiu et al., 2019).

4.3. Section summary

In Table 4, we classify CRSs into two classes in terms of the forms of input and output. Generally, interactive recommendations (Zou et al., 2020a; Wang et al., 2020c; ZhangTong et al., 2019b; Ding et al., 2020), critiquing methods (Chen and Pu, 2012; Wu et al., 2019a; Luo et al., 2020b; LuoScott et al., 2020), and CRSs focusing on the multi-turn conversation strategy (Christakopoulou et al., 2016, 2018; Lei et al., 2020a, 2020b; Li et al., 2021b) are prone to use the pre-annotated input and rule-based or template-based output; dialogue systems (Young et al., 2018; Zhou et al., 2018c; Gao et al., 2020) and CRSs caring about the dialogue ability (Li et al., 2018; Chen et al., 2019bb; Zhou et al., 2020a) are more likely to use raw natural language as input and automatically generate responses. In the future, user understanding and response generation in CRSs will remain a critical research field, as they serve as the interface of CRSs and directly impact the user experience.

5. Exploration-exploitation trade-offs

One challenge of CRSs is to handle the cold-start users that have few historical interactions. A natural way to tackle this is through the idea of the Exploration-Exploitation (E&E) trade-off. With exploitation, the system takes advantage of the best option that is known; with exploration, the system takes some risks to collect information about unknown options. In order to achieve long-term optimization, one might make a short-term sacrifice. In the early stages of E&E, an exploration trial could be a failure, but it warns the model to not take that action too often in the future. Although the E&E trade-off is mainly used for the cold-start scenario in CRSs, it can also be used for improving the recommendation performance for any users (including cold users and warm-up users) in recommendation systems.

MAB is a classic problem formulated to illustrate the E&E trade-off, and many algorithms have been proposed to solve the problem. In CRSs, the MAB-based algorithms are introduced to help the system improve its recommendation. Besides, there are also CRSs that use meta-learning to balance E&E. We first introduce MAB and common MAB-based algorithms in recommender systems, then we present examples how CRSs balance E&E in their models.

5.1. Multi-armed bandits in recommendation

We first introduce the general MAB problem and the classic methods to solve it, then we introduce how recommender systems use MAB-based methods to achieve the E&E balance.

5.1.1. Introduction to multi-armed bandits

MAB is a classic problem that well demonstrates the E&E dilemma (Kephakis and Veinott, 1987; Auer et al., 2002). The name comes from the story where a gambler at a row of slot machines (each of which is known as a “one-arm bandit”) wants to maximize his expected gain and has to decide which machines to play, how many times to play each machine, in which order to play them, and whether to continue with the

current machine or try a different machine. The problem is difficult because all of the slot machines are black boxes, whose properties, i.e., the probability of winning, can only be estimated by the rewards observed in previous experiments.

Formally, the problem is to maximize the cumulative reward $\sum_{t=1}^T r_{a,t}$ after T rounds of arm selection. Here, $r_{a,t}$ is the reward with arm $0 \leq a \leq K$ selected at trial t , K is the total number of arms. Fig. 6 illustrates an example in which a gambler decides which arm to choose now. For a certain arm, a reward distribution is estimated based on previous experiment results. The gambler can, naturally, select to exploit the second arm which has the maximal mean reward $\mu(a)$. Or, he can take some risks to explore the other arm, e.g., the third arm, which has a higher uncertainty $\Delta(a)$ and thus has the maximal upper confidence bound (UCB) of the reward $\mu(a) + \Delta(a)$. After each time he plays an arm, the new reward value is observed, and the estimated reward distribution of this arm can be updated accordingly. With exploration, the gambler hopes to find the potential arms that have higher rewards, though it can also end up in lower rewards. In any case the gambler has a better estimation of the rewards of those arms.

Equivalently, the problem can also be formulated as minimizing the regret function, which is the difference between the theoretically optimal expected cumulative reward and the estimated expected cumulative reward:

$$\mathbf{E}\left[\sum_{t=1}^T r_{t,a^*}\right] - \mathbf{E}\left[\sum_{t=1}^T r_{t,a}\right], \quad (5)$$

where a^* is the theoretically optimal arm with the maximum expected reward at all times.

The commonly used bandit strategies include the greedy strategy, i.e., the exploit-only strategy that always selects the arm with the current estimated highest reward; the random strategy, i.e., a trivial explore-only strategy; and ϵ -greedy, which mixes the greedy and random strategies via a trigger with probability ϵ . Other classic models include Upper Confidence Bound (UCB) (Auer, 2002; Auer et al., 2002) and Thompson Sampling (TS) (Chapelle and Li, 2011) which are introduced next.

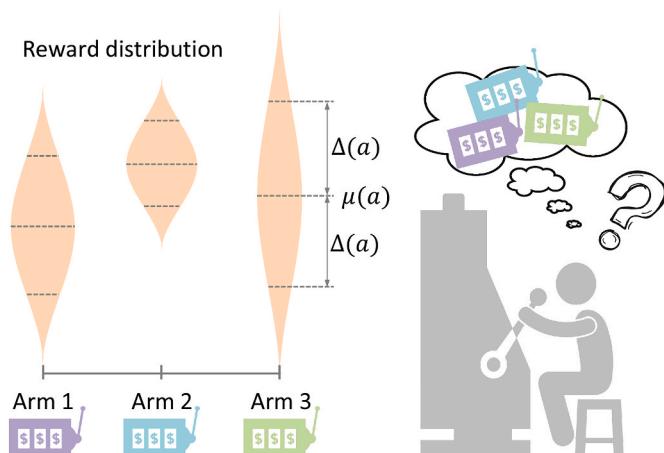


Fig. 6. An illustration of the multi-armed bandit problem.

5.1.2. Recommendation via MAB-based methods

As the classic algorithm for E&E trade-offs, MAB-based models can be seamlessly plugged into the online recommendation setting (Zeng et al., 2016; Zheng et al., 2018), interactive recommendation (Zhao et al., 2013; Wang et al., 2017), and CRSs (Christakopoulou et al., 2016; Zhang et al., 2020c; Li et al., 2021b). In the online or interactive recommendation tasks, the system aims to recommend the optimal item (s) according to users' previous feedback. This process can be deemed as a MAB problem, where each arm corresponds to an item. Therefore, the classical MAB-based methods can be plugged in this situation.

However, traditional bandit methods only consider treating items as independent arms and ignore the item features (Li et al., 2010). Directly estimating each item's probability of being chosen based on the accumulated rewards is rather inefficient due to a large number of items. In recommendation, there is a rich set of features on users and items, and whether a user u_t would choose item a_t can be predicted by the features of both u_t and a_t . Motivated by this, Li et al. (2010) propose a linear contextual bandit model called LinUCB, which is the first bandit model that considers the contextual information (i.e., user/item features) in recommendation systems.

For each trial t , they assume the expected reward r_t of a user u_t choosing an arm (item) a_t is linear in its d -dimensional feature vector \mathbf{x}_{u_t, a_t} with the unknown coefficient vector θ_a^* (which is determined on this arm a_t rather than other arms); namely, for all trial t ,

$$\mathbb{E}[r_{t,a} | \mathbf{x}_{u_t, a_t}] = \mathbf{x}_{u_t, a_t}^\top \theta_a^*, \quad (6)$$

where the feature vector \mathbf{x}_{u_t, a_t} summarizes information of both user u_t and arm (item) a_t , and is referred to as the context. The coefficients θ_a^* can be learned from the historical interactions and feedback. Specifically, let \mathbf{D}_a be a design matrix of dimension $m \times d$ at trial t , e.g., m contexts that are observed previously for arm a , and $\mathbf{c}_a \in \mathbb{R}^m$ be the corresponding reward vector, the coefficients θ_a^* are estimated by applying ridge regression to the training data $(\mathbf{D}_a, \mathbf{c}_a)$ as:

$$\hat{\theta}_a = (\mathbf{D}_a^\top \mathbf{D}_a + \mathbf{I}_d)^{-1} \mathbf{D}_a^\top \mathbf{c}_a,$$

where \mathbf{I}_d is the $d \times d$ identity matrix. When components in \mathbf{c}_a are independent conditioned on corresponding rows in \mathbf{D}_a , it can be shown that with probability at least $1 - \delta$,

$$\left| \mathbf{x}_{u_t, a_t}^\top \hat{\theta}_a - \mathbb{E}[r_{t,a} | \mathbf{x}_{u_t, a_t}] \right| \leq \alpha \sqrt{\mathbf{x}_{u_t, a_t}^\top (\mathbf{D}_a^\top \mathbf{D}_a + \mathbf{I}_d)^{-1} \mathbf{x}_{u_t, a_t}},$$

for any $\delta > 0$ and $\mathbf{x}_{u_t, a_t} \in \mathbb{R}^d$, where $\alpha = 1 + \sqrt{\ln(2/\delta)/2}$ is a constant. Therefore, the inequality gives a reasonably tight UCB for the expected reward of arm a_t , from which the arm-selection (recommendation) strategy can be derived: at each trial t , choose

$$a_t \stackrel{\text{def}}{=} \arg \max_{a \in \mathcal{A}_t} \left(\mathbf{x}_{u_t, a_t}^\top \hat{\theta}_a + \alpha \sqrt{\mathbf{x}_{u_t, a_t}^\top (\mathbf{D}_a^\top \mathbf{D}_a + \mathbf{I}_d)^{-1} \mathbf{x}_{u_t, a_t}} \right).$$

Actually, the contextual bandit model improves the recommendation by leveraging the user/item features through the idea of collaborative filtering (SarwarGeorge et al., 2001; Schafer et al., 2007), i.e., those items are more likely to be recommended to a user who showed preference for items with similar features.

There are also studies pointing out that exploration in recommendations is important, i.e., the recommendations should be diverse instead of being limited by similar items (Qin et al., 2014; Liu et al., 2020bb; Ding et al., 2020). For instance, Ding et al. (2020) consider the fact that users may have different preference with regard to the diversity of items, e.g., a user with specific interest may prefer a relevant item set than a diverse item set, while another user without specific interest may prefer a diverse item set to explore his interests. Therefore, the authors propose a bandit learning framework to consider the user's preferences on both the item relevance features and the diversity features. It is a way

to trade off the accuracy and diversity of recommendation results.

Besides, Yu et al. (2019b) use a cascading bandit in a visual dialogue augmented interactive recommender system. In cascading bandits, the user examines the recommended list from the first item to the last and selects the first attractive one (Kveton et al., 2015; Zong et al., 2016). This setting is practical to implement in online recommender systems or search engines. It has an excellent advantage as it can provide reliable negative samples, which are critical for recommendation, and the problem has drawn a lot of research attention (Chen et al., 2019; Ding et al., 2019; Wang et al., 2020c; LianQi and Chen, 2020; Chen et al., 2019). Since the system can ensure that the items before the first selected one are not attractive, thus it can easily obtain reliable negative samples. Another contribution is the use of the item's visual appearance and user feedback to design more efficient exploration.

In addition, there are other efforts to enhance bandit methods in different recommendation scenarios. For instance, Chou et al. (2015) indicate that a user would only choose one or a few arms in the candidates, leaving out the informative non-selected arms. They propose the concept of pseudo-rewards, which embeds estimates to the hidden rewards of non-selected actions under the bandit setting. Wang et al. (2018) consider dependencies among items and explicitly formulate the item dependencies as clusters on arms, where arms within a single cluster share similar latent topics. They adopt a generative process based on a topic model to explicitly formulate the arm dependencies as the clusters on arms, where dependent arms are assumed to be generated from the same cluster. Yang et al. (2020) consider the situations where there are exploration overheads, i.e., there are non-zero costs associated with executing a recommendation (arm) in the environment, and hence, the policy should be learned with a fixed exploration cost constraint. They propose a hierarchical learning structure to address the problem. Sakhri et al. (2020) state that the online bandit signal is sparse and uneven, so they utilize the massive offline historical data. The difficulty is that most of offline data is irrelevant to the recommendation task, and the authors propose a probabilistic model to solve it.

The advantage of multi-armed bandit methods is their ability to conduct online learning, enabling the model to learn the preferences of cold users and adjust the strategy quickly after several trials to pursue a global optimum.

5.2. Multi-armed bandits in CRSs

The ability to interact with users enables CRSs to directly use MAB-based methods to help the recommendation. Christakopoulou et al. (2016) propose a classic CRS based on MAB, which uses several naive MAB-based methods to enhance the offline probabilistic matrix factorization (PMF) model (Salakhutdinov and Mnih, 2007). They first initialize the model parameters using offline data, then leverage real-time user feedback to update parameters via several common multi-armed bandit models, including the aforementioned greedy strategy, random strategy, UCB (Auer, 2002; Auer et al., 2002), and TS (Chapelle and Li, 2011). On the one hand, the performance improves on the initialized model due to the online updating; on the other hand, the offline initialization helps bandit methods reduce the computational complexity.

As mentioned above, the original MAB methods ignore item features, which could be very helpful in recommendation. Hence, Zhang et al. (2020c) propose a conversational upper confidence bound (ConUCB) algorithm to apply the LinUCB model (Li et al., 2010) in the CRS context. Instead of asking items, ConUCB asks the user about one or more attributes (key-terms in their work). Specifically, they make the assumption that user preference on attributes can propagate to items, hence the system can analyze user feedback on queried attributes to quickly narrow down the item candidates. The strategies to select the attributes and arms depend on both the attribute-level and arm-level rewards, i.e., the feedback on attributes and items will be absorbed into the model parameters for future use. In addition, the authors employ a hand-crafted

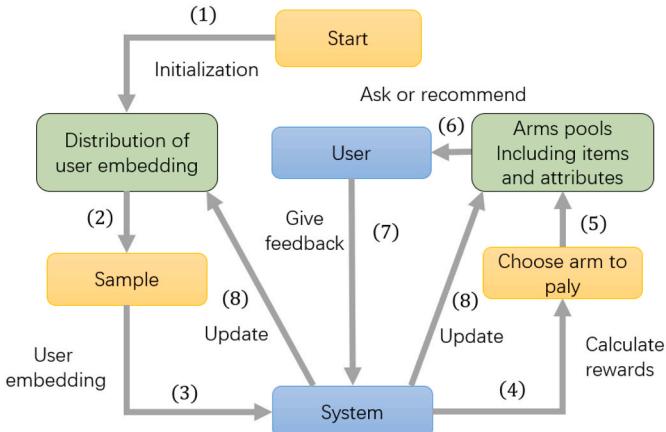


Fig. 7. The flowchart of the ConTS algorithm. Credits: Li et al. (Li et al., 2021b).

function to determine the timing to ask attributes or make recommendation, e.g., making k conversations in every m rounds.

However, hand-crafted strategies are fragile and inflexible, as the system should make recommendation only when the confidence is high. Therefore, Li et al. (2021b) propose a Conversational Thompson Sampling method (ConTS) to automatically alternate asking questions about attributes with recommending items. They achieve this goal by unifying all attributes and items in the same arm pool, thus an arm selected from the arm pool can be either a recommendation about an item or a question about an attribute. The flowchart of ConTS is illustrated in Fig. 7. ConTS assumes each user's preference vector $\tilde{\mathbf{u}}$ is sampled from a prior Gaussian distribution as $\tilde{\mathbf{u}} \sim \mathcal{N}(\mu_u, l^2 \mathbf{B}_u^{-1})$, where the μ_u , \mathbf{B} , and l are parameters.

For each new-coming user, the mean of prior Gaussian distribution, μ_u is initialized by the average of existing users' preference vector \mathcal{U}^{old} as:

$$\mu_u = \frac{1}{|\mathcal{U}^{\text{old}}|} \sum_{i=1}^{|\mathcal{U}^{\text{old}}|} \mathbf{u}_i, \quad \mathbf{u}_i \in \mathcal{U}^{\text{old}}. \quad (7)$$

The expected reward of arm a (which can either be an item or an attribute) for user u is also formulated as a Gaussian distribution since the Gaussian family is conjugate to itself. The expected reward is written as:

$$r(a, u, \mathcal{P}_u) \sim \mathcal{N}\left(\tilde{\mathbf{u}}^\top \mathbf{x}_a + \sum_{p_i \in \mathcal{P}_u} \mathbf{x}_a^\top \mathbf{p}_i, l^2\right), \quad (8)$$

where \mathcal{P}_u denotes the user's currently known preferred attributes obtained in historical conversations. And \mathbf{x}_a represents the embedding vector of an arm. In the reward function, the term $\tilde{\mathbf{u}}^\top \mathbf{x}_a$ models the general preference of user u to arm a , and the term $\sum_{p_i \in \mathcal{P}_u} \mathbf{x}_a^\top \mathbf{p}_i$ models the affinity between arm a and the user's preferred attributes \mathcal{P}_u . Then ConTS select an arm with the maximal reward as:

$$a(t) = \operatorname{argmax}_{a \in \mathcal{A}_u} \tilde{\mathbf{u}}^\top \mathbf{x}_a + \sum_{p_i \in \mathcal{P}_u} \mathbf{x}_a^\top \mathbf{p}_i. \quad (9)$$

Note that if the $a(t)$ is an attribute, the system will query the user about the preference on this attribute; if it is an item, the system will make a recommendation using this item. After obtaining users' feedback, parameters such as $\mu_u, \mathcal{P}_u, \mathbf{B}$ will be updated accordingly.

5.3. Meta learning for CRSs

Beyond multi-armed bandits, there are work trying to balance

between exploration and exploitation via meta learning. For instance, Zou et al. (2020b) formulate the interactive recommendation as a meta-learning problem, where the objective is to learn a learning algorithm that takes the user's historical interactions as the input and outputs a model (policy function) that can be applied to new users. The authors follow the idea of meta reinforcement learning (DuanJohn Schulman et al., 2016) and use Q-Learning (Mnih et al., 2013) to learn the recommendation policy. The exploration strategy is the aforementioned ϵ -greedy, where the model will select the items of maximum Q-value with probability $1 - \epsilon$, and choose random items with probability ϵ .

In addition, Lee et al. (LeeJinbae et al., 2019) address the cold-start problem in recommendation via a model based on the Model-Agnostic Meta-Learning (MAML) algorithm (Finn et al., 2017). The learned recommendation model can quickly adapt to the cold user preference in the fine-tuning stage by asking the cold user a few questions about certain items (called the evidence candidates in the work). A drawback of this work is that the evidence candidates are only selected once, and the query process is conducted only at the beginning when cold users arrived. It could be better to extend this strategy to a CRS setting and develop a dynamic multi-round query strategy to further enhance the recommendation.

5.4. Section summary

In this section, we introduce how a CRS can solve the cold-start problem and trade off the E&E balance via the interactive models such as MAB-based methods and meta learning methods. The solutions are summarized in Table 5. It still has a lot of room for CRSs to develop potential models to address the E&E problem, in order to improve the user experience.

6. Evaluation and user simulation

In this section, we discuss how to evaluate CRSs, which is an underexplored problem. We group attempts to evaluate CRSs into two classes: (1) Turn-level evaluation, which evaluates a single turn of the system output, including the recommendation task and response generation task, which are both supervised prediction tasks. (2) Conversation-level evaluation, which evaluates the performance of the multi-turn conversation strategy which is a sequential decision making task. To achieve the goal, user simulation is important. We first introduce the commonly used datasets in CRSs, and then we introduce the metrics, methods, and problems in the turn-level and conversation-level evaluation of CRSs. Finally, we discuss the strategies of user simulation in CRSs.

6.1. Datasets and tools

We list the statistics of the commonly used CRS datasets in Table 6. Some studies collect human-human and human-machine conversation data by asking true users to converse using natural language under certain rules. To guarantee the quality of the data, these users will be rewarded after providing qualified data. There are crowdsourcing sites, such as Amazon Mechanical Turk (AMT),⁵ where the researchers can find participants to fulfill their data collection task (Li et al., 2018; Moon et al., 2019; Liu et al., 2020ab; Hayati et al., 2020).

As mentioned earlier, a lot of studies of CRS focus on the interaction policy and the recommendation strategy instead of language understanding and generation. Thus, all these studies need is the labeled entities (including users, items, attributes, etc.) in the multi-turn conversation (Zhang et al., 2018; Christakopoulou et al., 2018; Lei et al., 2020a, 2020b; Li et al., 2021b; Fu et al., 2021). These studies mainly

⁵ <https://www.mturk.com/>.

Table 5

E&E-based methods adopted by interactive recommender systems (IRSSs) and CRSs.

Mechanism		Publications
MAB in IRSSs	Linear UCB considering item features Considering diversity of recommendation Cascading bandits providing reliable negative samples Leveraging social information Combining offline data and online bandit signals Considering pseudo-rewards for arms without feedback Considering dependency among arms Considering exploration overheads	Li et al. (2010) (Qin et al., 2014; Liu et al., 2020bb; Ding et al., 2020) (Kveton et al., 2015; Zong et al., 2016) Yu et al. (2019b) Sakhi et al. (2020) Chou et al. (2015) Wang et al. (2018) Yang et al. (2020)
MAB in CRSs	Traditional bandit methods in CRSs Conversational upper confidence bound Conversational Thompson Sampling Cascading bandits augmented by visual dialogues	Christakopoulou et al. (2016) Zhang et al. (2020c) Li et al. (2021b) Yu et al. (2019b)
Meta learning for CRSs	Learning to learn the recommendation model	(LeeJinbae et al., 2019; Zou et al., 2020b; Wei et al., 2020)

Table 6

Statistics of commonly used datasets of CRSs.

Dataset	#Dialogs	#Turns	Dialogue Type	Domains	Dialogue Resource	Related Publications
MovieLens (Bertin-Mahieux et al., 2011)	Depended on the dialogue simulation process		Movie	From item ratings	(Zhao et al., 2013; LoeppTim Hussein and Ziegler, 2014; Vendrov et al., 2020; Zou et al., 2020b), (LeeJinbae et al., 2019; Iovine et al., 2020; Habib et al., 2020)	
LastFM (Bertin-Mahieux et al., 2011)			Music	From item ratings	(Lei et al., 2020a, 2020b; Zhou et al., 2020b)	
Yelp			Restaurant	From item ratings	(Sun and Zhang, 2018; Lei et al., 2020a, 2020b)	
Amazon (McAuley et al., 2015b)			E-commerce	From item ratings	(Zhang et al., 2018; Fu et al., 2020; Zou et al., 2020; Penha and Hauff, 2020), (Wu et al., 2019a; Luo et al., 2020b; LuoScott et al., 2020a; Fu et al., 2021)	
TG-ReDial (Zhou et al., 2020c)	10,000	129,392	Rec., chitchat	Movie, multi topics	From item rating, and enhanced by multi topics	Zhou et al. (2020c)
Facebook_Rec (Dodge et al., 2016)	1M	6M	Rec.	Movie	From item ratings	Dodge et al. (2016)
COOKIE (Fu et al., 2020)	Not given	11,638,418	Rec.	E-commerce	From interactions and reviews on Amazon dataset (McAuley et al., 2015b)	Fu et al. (2020)
HOOPS (Fu et al., 2021)	Not given	11,638,418	Rec.	E-commerce	From interactions and reviews on Amazon dataset (McAuley et al., 2015b)	Fu et al. (2021)
DuRecDial (Liu et al., 2020ab)	10,190	155,477	Rec., QA, etc.	Movie, restaurant, etc.	Generated by workers	(Liu et al., 2020ab)
OpenDialKG (Moon et al., 2019)	15,673	91,209	Rec. chitchat	Movie, book, sport, etc.	Generated by workers	Moon et al. (2019)
ReDial (Li et al., 2018)	10,006	182,150	Rec., chitchat	Movie	Generated by workers	(Li et al., 2018; Chen et al., 2019bb; Zhou et al., 2020a; Ma et al., 2020)
MGConvRex (Xu et al., 2020)	7.6K+	73K	Rec.	Restaurant	Generated by workers	Xu et al. (2020)
GoRecDial (Kang et al., 2019; Ma et al., 2020)	9,125	170,904	Rec.	Movie	Generated by workers	Kang et al. (2019)
INSPIRED (Hayati et al., 2020)	1,001	35,811	Rec.	Movie	Generated by workers	Hayati et al. (2020)
ConveRSE (Iovine et al., 2019)	Not given	9,276	Rec.	Movie, books, music	Generated by workers	(Iovine et al., 2019, 2020)

simulate and construct the user interaction from the historical records in traditional recommendation datasets, e.g., MovieLens (Bertin-Mahieux et al., 2011), LastFM (Bertin-Mahieux et al., 2011), Yelp,⁶ and Amazon dataset (McAuley et al., 2015b).

Although it seems to be many datasets in CRSs, these datasets are not qualified to develop the CRSs that can work in industrial applications. The reason is twofold: first, the scale of these datasets is not enough to cover the real-world entities and concepts; second, the conversation is

either constructed from the non-conversation data or generated under certain rigorous constraints, so it is hard to generalize to the complex and diverse real-world conversations. Therefore, more effort is needed to develop large-scale, generalizable, natural datasets for CRSs. Therefore, more effort is still needed to develop large-scale, generalizable, diverse, and natural datasets for CRSs.

There are many different settings in CRSs, making comparison between different models difficult. Recently, Zhou et al. (2021) have

⁶ <https://www.yelp.com/dataset>.

implemented an open-source toolkit, called CRSLab,⁷ for building and evaluating CRSs. They unify the tasks in existing CRSs into three sub-tasks: namely recommendation, conversation and policy, which correspond to our three components in Fig. 3: recommendation engine, user interface, and conversation strategy module, respectively. Some models and metrics are implemented under the three tasks, and the toolkit contains an evaluation module that can not only conduct the automatic evaluation but also the human evaluation through an interaction interface, which makes the evaluation of CRSs more intuitive. However, up to now, the majority of implemented methods are based on end-to-end dialogue systems (Li et al., 2018; Chen et al., 2019bb; Zhou et al., 2020a) or deep language models (Zhou et al., 2020c); the CRSs that focus on the interaction policy and the multi-turn conversation strategies ((Lei et al., 2020b; Lei et al., 2020a)) are absent.

6.2. Turn-level evaluation

The fine-grained evaluation of CRSs is conducted on the output of each single turn, which contains two tasks: language generation and recommendation.

6.2.1. Evaluation of language generation

For CRS models that generate natural language-based responses to interact with users, the quality of the generated responses is critical. Thus we can adopt the metrics used in dialogue response generation to evaluate the output of CRS. Two example metrics are BLEU (Papineni et al., 2002a) and Rouge (Lin, 2004). BLEU measures the precision of generated words or n-grams compared to the ground-truth words, representing how much the words in the machine-generated utterance appeared in the ground-truth reference utterance. Rouge measures the recall of it, i.e., how many of the words or n-grams in the ground-truth reference utterance appear in the machine-generated utterance.

However, it is widely debated whether these metrics are suitable for evaluating language generation (Liu et al., 2016a; Novikova et al., 2017). Because those metrics are only sensitive to lexical variation, they cannot appropriately assess semantic or syntactic variations of a given reference. Meanwhile, the goal of the proposed system is not to predict the highest probability response, but rather the long-term success of the dialogue. Thus, other metrics reflecting user satisfaction are more suitable in evaluation, such as measuring fluency (CelikyilmazAntoine et al., 2018; Narayan et al., 2018; Du et al., 2017), consistency (Gandhe and Traum, 2008; Lapata and Barzilay, 2005), readability (Lapata, 2003), informativeness (Huang et al., 2017), diversity (Li et al., 2016b; Ippolito et al., 2019; Gao et al., 2019b), and empathy (Ghandeharioun et al., 2019; Sharma et al., 2021). For more metrics and evaluation methods on text generation, we refer the readers to the overviews (Celikyilmaz et al., 2020; Deriu et al., 2021).

However, the CRSs based on end-to-end dialogue frameworks or deep language models may have limitations regarding the usability in practice. Recently, Jannach and Manzoor (2020) conducted an evaluation on the two state-of-the-art end-to-end frameworks (Li et al., 2018; Chen et al., 2019bb), and showed that both models face three critical issues: (1) For each system, about one-third of the system utterances are not meaningful in the given context and would probably lead to a breakdown of the conversation in a human evaluation. (2) Less than two-thirds of the recommendations were considered to be meaningful in a human evaluation. (3) Neither of the two systems “generated” utterances, as almost all system responses were already present in the training data. Jannach and Manzoor (2020)’s analysis shows that human assessment and expert analysis are necessary for evaluating CRS models as there is no perfect metric to evaluate all aspects of a CRS. The CRS models and their evaluation still have a long way to go.

6.2.2. Evaluation of recommendation

The performance of recommendation models is evaluated by comparing the predicted results with the records in the test set. There are two kinds of metrics in measuring the performance of recommender systems:

- **Rating-based Metrics.** These metrics assume the user feedback is an explicit rating score, e.g., an integer in the range of one to five. Therefore, we can measure the divergence between the predicted scores of models and the ground-truth scores given by users in the test set. Conventional rating-based metrics include Mean Squared Error (MSE) and Root Mean Squared Error (RMSE), where RMSE is the square root of the MSE.
- **Ranking-based Metrics.** These metrics are more frequently used than rating-based metrics. Ranking-based metrics require that the relative order of predicted items should be consistent with the order of items in the test set. Thereby, there is no need for explicit rating scores from users, and the implicit interactions (e.g., clicks, plays) can be used to evaluate models. For example, a good evaluation result means that the model should only recommend the items in the test set, or it means that the items with higher scores in the test set should be recommended at higher ranks than the items with lower scores. Frequently used ranking-based metrics include hits, precision, recall, F1-score, Mean Reciprocal Rank (MRR), Mean Average Precision (MAP), and Normalized Discounted Cumulative Gain (NDCG) (Järvelin and Kekäläinen, 2002).

Recently, it has become common for researchers to speed up evaluation by sampling a small set of irrelevant items and calculate the ranking-based metrics only on the small set (He et al., 2017; Ebisu et al., 2018; Hu et al., 2018; Yang et al., 2018). However, Krichene and Rendle (2020) point out and prove that some metrics, such as average precision, recall, and NDCG, are inconsistent with the exact metrics when they are calculated on the sampled set. This means that if a recommender A outperforms a recommender B on the sampled metric, it does not imply that A has a better metric than B when the metric is computed exactly. Therefore, the authors suggest that sampling during evaluation should be avoided; if it is necessary to sample, using the corrected metrics proposed by the authors is a better choice.

The biggest problem in these evaluation methods is that real-world user interactions are very sparse, and a large fraction of items never have a chance of being consumed by a user. However, this does not mean that the user does not like any of them. Perhaps the user has never seen them, or the user just does not have resources to consume them (Liu et al., 2020aa; Chen et al., 2020a). Hence, taking the consumed items in the test set as the users’ ground-truth preferences can introduce evaluation biases (Yang et al., 2018; Chen et al., 2020a). Unlike static recommender systems, CRSs have the ability to ask real-time questions, so the system can make sure whether a user is satisfied with an item by collecting users’ online feedback. This online user test can avoid biases and provide conversation-level assessments for the CRS model.

6.3. Conversation-level evaluation

Different from the turn-level evaluation which compares the prediction results with the ground-truth labels in a supervised way, the conversation-level evaluation is not a supervised prediction task. The interaction process is not i.i.d. (independent and identically distributed) since each observation is part of a sequential process and each action the system makes can influence future observations. Plus, the conversation heavily relies on the user feedback. Therefore, the evaluation of the conversation requires either an online user test or leveraging historical interaction data which can be conducted by the off-policy evaluation or using user simulation.

⁷ <https://github.com/RUCAIBox/CRSLab>.

6.3.1. Online user test

The online user test, or A/B test, can directly evaluate the conversation policy by leveraging true user feedback. To conduct the assessment, the appropriate metrics should be designed. For example, the average turn (AT) is a global metric to optimize in a CRS, as the model should capture user intention and make successful recommendations thus finish the conversation with as few turns as possible (Lei et al., 2020a, 2020b; Li et al., 2021b). A similar metric is the recommendation success rate (SR@ t), which measures how many conversations have ended with the successful recommendation by the t -th turn. Besides, the ratio of failed attempts, e.g., how many of the questions asked by the system are rejected or ignored by users, can be a feasible way to measure whether a system makes decisions to the users' satisfaction.

Besides these global statistics, the cumulative performance of each turn of the conversation can also reflect the overall quality of the conversation. The expectation of the cumulative reward of a conversation policy can be written as:

$$J(\pi) = \mathbb{E}_{\tau \sim p_\pi(\tau)} \left[\sum_{t=0}^T \gamma^t r(s_t, a_t) \right], \quad (10)$$

where the conversation trajectory τ is a sequence of states and actions of length T , $p_\pi(\tau)$ is the trajectory distribution under policy π . $\gamma \in (0, 1]$ is a scalar discount factor. $r(s_t, a_t)$ is the immediate reward obtained by performing action a_t at state s_t , e.g., it can be a feedback signal that reflects user satisfaction such as user clicks or dwell time (Chen et al., 2019aa; Ie et al., 2019).

Though effective, the online user evaluation has critical problems: (1) The online interaction between humans and CRSs is slow and usually takes weeks to collect sufficient data to make the assessment statistically significant (Li et al., 2015; Gilotte et al., 2018; Zhao et al., 2019). (2) Collecting users' feedback is expensive in terms of engineering and logistic overhead (Jagerman et al., 2018, 2019; Xu et al., 2015) and may hurt user experience as the recommendation may not satisfy them (Schnabel et al., 2018; Li et al., 2015; Gilotte et al., 2018; Chen et al., 2019ab). Therefore, a natural solution is to leverage the historical interaction, where the off-policy evaluation and user simulation techniques can be used.

6.3.2. Off-policy evaluation

Off-policy evaluation, also called counterfactual reasoning or counterfactual evaluation, is designed to answer a counterfactual question: what would have happened if instead of π_β we would have used π_θ ? Specifically, when we want to evaluate the current target policy π_θ but we only have data under a behavior policy (or logging policy) π_β , we can still evaluate the target policy π_θ by introducing the importance sampling or inverse propensity score (Gilotte et al., 2018; Jagerman et al., 2019; Chen et al., 2019aa; McInerney et al., 2020; Levine et al., 2020) as:

$$J(\pi_\theta) = \mathbb{E}_{\tau \sim \pi_\beta(\tau)} \left[\frac{\pi_\theta(\tau)}{\pi_\beta(\tau)} \sum_{t=0}^T \gamma^t r(s, a) \right]. \quad (11)$$

It is similar to Equation (10) except we use data logged under another policy to evaluate the target policy. Where a weight $w(\tau) = \frac{\pi_\theta(\tau)}{\pi_\beta(\tau)}$ is used to address the distribution mismatch between the two policy π_β and π_θ . Unfortunately, such an estimator suffers from high variance when π_θ deviates from π_β a lot. The variance reduction techniques are introduced as the remedy. The common techniques include weight clipping (Chen et al., 2019aa; Zou et al., 2020a) which limits $w(\tau)$ by an upper bound, and trusted region policy optimization (TRPO) (Schulman et al., 2015; Chen et al., 2019aa).

Another intuitive method is to directly simulate user behaviors just like the online user test, where user feedback is provided by the user simulators instead of true users. It is efficient and can avoid the high variance problem. However, the challenge is that the preference of simulated users may deviate from the true users, i.e., the user simulation

can avoid high variance, but it introduces bias. Therefore, creating reliable user simulators is a crucial challenge.

6.3.3. User simulation

There are generally four types of strategies in simulating users: (1) using the direct interaction history of users, (2) estimating user preferences on all items, (3) extracting from user reviews, and (4) imitating human conversational corpora.

- *Using Direct Interaction History of Users.* The basic idea is similar to the evaluation of traditional recommender systems, where a subset of human interaction data is set aside as the test set. If the items recommended by a CRS are in the users' test set, then this recommendation is deemed to be a successful one. As user-machine interactions are relatively rare, there is a need to generate/simulate interaction data for training and evaluation. Sun and Zhang (2018) make a strong assumption that users visit restaurants after chatting with a virtual agent. Based on this assumption, they create a crowdsourcing task to use a schema-based method to collect dialogue utterances from the Yelp dataset. In total, they collect 385 dialogues, and simulate 875, 721 dialogues based on the collected dialogues by a process called delexicalization. For instance, "I'm looking for Mexican food in Glendale" is converted to the template: "I'm looking for <Category> in ", then they use these templates to generate dialogues by using the rating data and the rich information on the Yelp dataset. Lei et al., 2020a, Lei et al., 2020b use click data in the LastFM and Yelp datasets to simulate conversational user interactions. Given an observed user-item interaction, they treat the item as the ground truth item to seek for and its attributes as the oracle set of attributes preferred by the user in this session. First, the authors randomly choose an attribute from the oracle set as the user's initialization to the session. The session goes into a loop of a "model acts – simulator responses" process, in which the simulated user will respond with "Yes" if the query entity is contained in the oracle set and "No" otherwise. Most CRS studies adopt this simulation method because of its simplicity (Zou et al., 2020; Christakopoulou et al., 2018; Chen et al., 2019ba). However, the sparsity problem in recommender systems still remains: only a few values in the user-item matrix are known, while most elements are missing, which forbids the simulation on these items.

- *Estimating User Preferences on All Items.* Using direct user interactions to simulate conversations has the same drawbacks as we mentioned above, i.e., a large number of items that have not been seen by a user are treated as disliked items. To overcome this bias in the evaluation process, some research proposes to obtain the user preferences on all items in advance. Given an item and its auxiliary information, the key to simulating user interaction is to estimate or synthesize preferences for this item. For example, Christakopoulou et al. (2016) ask 28 participants to rate 10 selected items, and then they can estimate the latent vectors of the 10 users' preferences based on their matrix factorization model. By adding noise to the latent vector, they simulate 50 new user profiles and calculate these new users' preferences on any items based on the same matrix factorization model. Zhang et al. (2020c) propose to use ridge regression to compute user preferences based on these known rewards on historical interaction and users' features; they synthesize the user's reaction (rewards) on each item according to the computed preferences. This kind of method can theoretically simulate a complete user preference without the exposure bias. However, because the user preferences are computed or synthesized, it could deviate from real user preferences. Huang et al. (2020) analyze the phenomenon of popularity bias (Steck, 2011; Pradel et al., 2012) and selection bias (Marlin et al., 2007; Hernández-Lobato et al., 2014; Steck, 2013) in simulators built on logged interaction data and try to alleviate model performance degradation due to these biases; it remains to be seen to

which degree generated interactions of the type described above are subject to similar bias phenomena.

- *Extracting Information from User Reviews.* Besides user behavior history, many e-commerce platforms have textual review data. Unlike the consumption history, an item's review data usually explicitly mentions attributes, which can reflect the users' personalized opinions on this item. Zhang et al. (2018) transform each textual review of part of the Amazon dataset into a question-answer sequence to simulate the conversation. For example, when a user mentioned that a blue Huawei phone with the Android system in a review of a mobile phone X, then the conversation sequence constructed from this review is (Category: mobile phone → System: Android → Color: blue → Recommendation: X). Zhou et al. (2020c) also construct simulated interactions by leveraging user reviews. Based on a given user profile and its historical watching records, the authors construct a topic thread that consists of topics (e.g., “family” or “job seeking”) extracted from reviews of these watched movies. The topic thread is organized by a rule and eventually leads to the target movie. And the synthetic conversation is fleshed out by retrieving the most related reviews under corresponding topics.

A noteworthy problem is that the aspects mentioned in reviews may contain some drawbacks of the products, which does not aid understanding why a user has chosen a product. For example, when a user complains about the capacity of a phone of 64 Gigabytes is not enough, and it should not be simply convert to (Storage capacity: 64 Gigabytes) for the CRS to learn. Thus, employing sentiment analysis on the review data is necessary, and only the attribute with positive sentiment should be considered as the reason in choosing the item (Zhang et al., 2014a, 2014b).

- *Imitating Humans' Conversational Corpora.* In order to generate conversational data without biases, a feasible solution is to use real-world two-party human conversations as the training data (Vakulenko et al., 2020a). By using this type of data, a CRS system can directly mimic human behavior by learning from a large number of real human-human conversations. For example, Li et al. (2018) ask workers from AMT to converse in terms of the topics on the movie recommendation. Using these conversational corpora as training data, the model can learn how to respond properly based on the sentiment analysis result. Liu et al. (Liu et al., 2020ab) conduct a similar data collection process. Except for collecting the dialogues about the recommendation, they also collect and construct a knowledge graph and define an explicit profile for each worker who seeks recommendations. Therefore, the conversational topics can

contain many non-recommendation scenarios, e.g., question answering or social chitchat, which are more common in real life. To evaluate this kind of model, besides considering whether the user likes the recommended item, we have to consider if the system responds properly and fluently. The BLEU score (Papineni et al., 2002b) is used to measure the fluency of these models mimicking human conversations (Budzianowski et al., 2018; Zhang and OuZhou, 2020).

There are also drawbacks for this kind of method. First, when collecting the human conversational corpus, two workers need to enter the task at the same time, which is a rigorous setting and thus limits the scale of the dataset. Second, designers usually have many requirements that restrict the direction of the conversation. Therefore, the generated conversation is constrained and cannot fully cover the real-world scenarios. By imitating a collected corpus, learning a conversation strategy is very sensitive to the quality of the collected data. Vakulenko et al. (2020a) analyze the characteristics of different human-human corpora, e.g., in terms of initiative taking, and show that there are important differences between human-human and human-machine conversations.

Recently, Zhang and Balog (2020) have investigated using user simulations in evaluating CRSs. They organize the action sequence of the simulated user as a stack-like structure, called the user agenda. A dynamic update of the agenda is regarded as a sequence of pull or push operations, where dialogue actions are removed from or added to the top. Fig. 8 shows an example of a dialogue between the simulated user and a CRS. At each turn, the simulated user updates its agenda by either a push or a pull operation based on the dialogue state and the CRS's action. The authors define a set of actions and the transition rule on these actions to let the simulated user imitate real users' intentions. For example, the *Disclose* action indicates that the user expresses its need either actively, or in response to the agent's question, e.g., “I would like to arrange a holiday in Italy”. And after this action, the simulator can either transit to the *Inquire* action or the *Reveal* section based on how the CRS model acts.

Besides modeling the user preference in simulation, another branch of studies considers modeling user behaviors in the slate, top-*K*, or list-wise recommendation. A natural solution is to consider the combinatorial action which contains a list of items instead of a single item (Sunehag et al., 2015). However, this method is unable to scale to problems of the size encountered in large, real-world recommender systems. The feasible way is to assume a user only consumes a single item from each slate and the obtained reward only depends on the item

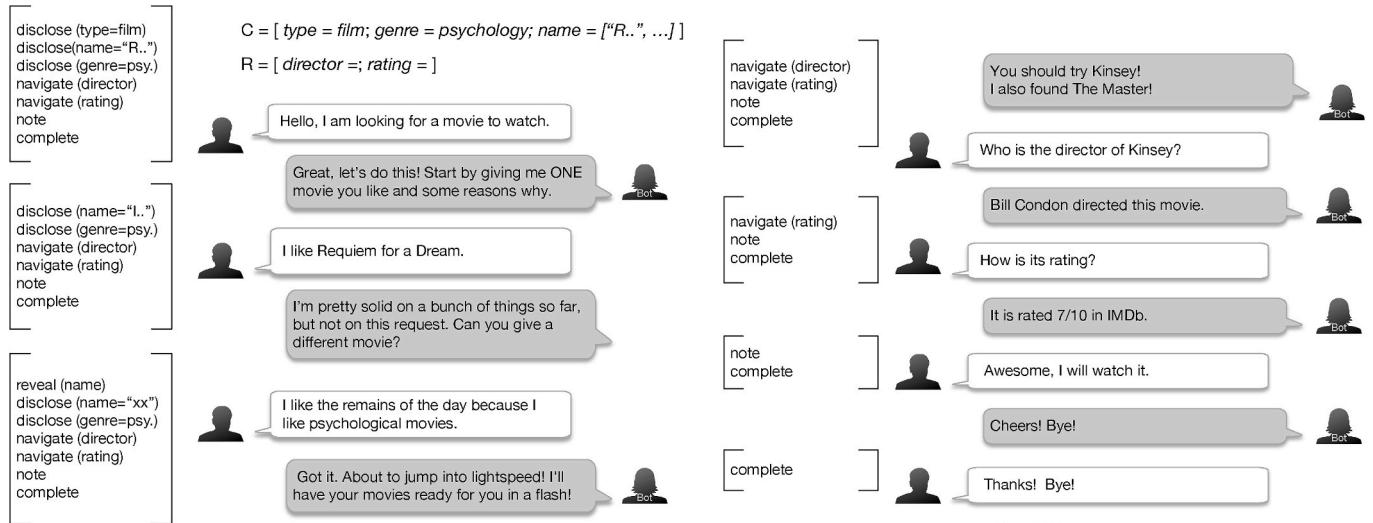


Fig. 8. Example dialogue with agenda sequence and state transition. The agenda is shown in square brackets. The third agenda is a result of a push operation, all other agendas updates are pull operations. Credits: Zhang and Balog (Zhang and Balog, 2020).

([He et al., 2019](#)). Under the assumption, user choice behavior can be modeled as the multinomial logit model ([Louviere et al., 2000](#)) or the cascade model ([He et al., 2019; Yu et al., 2019b; Kveton et al., 2015; Zong et al., 2016](#)). Despite the recent interest in developing reliable user simulators, we believe that the research in this field is in its infancy and needs a lot of advancements.

6.4. Section summary

In this section, we review the metrics, methods, and challenges in the turn-level evaluation and conversation-level evaluation of CRSs. The turn-level evaluation measures the performance of the supervised prediction tasks, i.e., recommendation and language generation of the CRS in a single round; the conversation-level evaluation measure how the conversation strategy performs in the multi-turn conversation. Since an online user test is expensive to conduct, researchers either leverage the off-policy evaluation which assesses the target policy using the logged data under the behavior policy, or directly introduce user simulators to replace the true users in evaluation.

The evaluation of CRSs still needs a lot of effort. It ranges from constructing large-scale dense conversational recommendation data, to proposing uniform evaluation methods to compare different CRS methods that integrate both recommendation and conversation aspects.

7. Future directions and opportunities

Having described key advances and challenges in the area CRSs, we now envision some promising future directions.

7.1. Jointly optimizing three tasks

The recommendation task, language understanding and generation task, and conversation strategies in CRSs are usually studied separately in the three components in [Fig. 3](#), respectively. The three components share certain objectives and data with each other ([Chen et al., 2019bb; Ma et al., 2020; Lei et al., 2020a; Zhou et al., 2020a](#)). For example, the user interface feeds extracted aspect-value pairs to the recommendation engine, and then integrates the entities produced by the recommendation engine into the generated response. However, they have the exclusive data that does not benefit each other. For instance, the user interface may use the rich semantic information in reviews but not shares with a recommendation engine ([Li et al., 2018](#)). Besides, the two components may work in the end-to-end framework that lacks an explicit conversation strategy to coordinate them in the multi-turn conversation ([Li et al., 2018; Chen et al., 2019bb](#)), thus the performance is not satisfied in human evaluation ([Jannach and Manzoor, 2020](#)).

Thereby, the three tasks should be jointly learned and guided by an explicit conversation strategy for their mutual benefit, for instance, what if the conversation strategy module were able to plan future dialogue acts based on item-item relationships (such as complementarity and substitutability ([McAuley et al., 2015a; Wan et al., 2018; Liu et al., 2020ba](#)))?

7.2. Bias and debiasing

It is inevitable that a recommender system could encounter various types of bias ([Chen et al., 2020a](#)). Some types of biases, e.g., popularity bias ([Abdollahpouri and Mansouri, 2020; Steck, 2011](#)) and conformity bias ([Zhang et al., 2014b; Liu et al., 2016b](#)), can be removed with introducing the interaction between the user and system. For example, a static recommender may not be sure whether a user will follow the crowd and like popular items. Therefore, the popularity bias is introduced in the recommender system since popular items can have higher probability of being recommended. This, however, could be avoided in CRSs because a CRS can query about the user's attitude towards popular

items in real time and avoid recommending them if the user gives negative feedback.

Nevertheless, some types of bias persist. For example, even though a recommender system may provide access to a large number of items, a user can only interact with a small set of them. If these items are chosen by a model or a certain exposure mechanism, users have no choices but to keep consuming these items. That is the exposure bias ([Liu et al., 2020aa](#)). Moreover, users often select or consume their liked items and ignore these disliked ones even these items have been exposed to users, which introduces the selection bias ([Marlin et al., 2007; Hernández-Lobato et al., 2014; Steck, 2013](#)), also known as the positivity bias ([Huang et al., 2020; Pradel et al., 2012](#)), i.e., rating data is often missing not at random and the missing ones are more likely to be disliked by the user ([Hernández-Lobato et al., 2014](#)). These types of bias can be amplified in the feedback loop and may hurt the recommendation model ([Sinha et al., 2016; Sun et al., 2019](#)). For instance, a CRS model polluted by biased data might repeatedly generate the same items even through users suggested they would like other ones.

There are relatively few efforts to study the bias problem in CRSs. The exploration-exploitation methods introduced in [Section 5](#) can alleviate some types of bias in CRSs. And [Huang et al. \(2020\)](#) make an attempt to remove the positivity bias in the user simulation stage for the interactive recommendation. Moreover, [Chen et al. \(2020a\)](#) present a comprehensive survey of different types of bias and describe a number of debiasing methods for recommender systems (RSs); it provides some perspectives for debiasing CRSs.

7.3. Sophisticated multi-turn conversation strategies

The multi-turn strategy considered in current studies of CRSs are relatively naive. For example, there is work using a hand-crafted function to determine the timing to ask attributes or make recommendation, e.g., making k conversations in every m rounds ([Zhang et al., 2020c](#)). These studies based on end-to-end dialogue systems or deep neural language models are worse: they do not even have an explicit strategy to control the multi-turn conversation ([Li et al., 2018; Chen et al., 2019bb](#)). Besides, some strategies can be problematic in regard to handling users' negative feedback. For instance, [Lei et al. \(2020a\)](#) consider updating the model parameters when the user dislikes a recommended item. However, simply taking rejected items as negative samples would influence the model's judgement on the queried attributes. For example, a user's rejection of a recreation video might be due to the fact that they watched it before, and it does not mean that they dislike recreation videos. To overcome this problem, the model should consider more sophisticated strategies such as recognizing reliable negative samples ([Chen et al., 2019; Ding et al., 2019; Wang et al., 2020c; LianQi and Chen, 2020; Chen et al., 2019](#)) as well as disentangling user preferences on items and attributes ([MaChang et al., 2019; Wang et al., 2020b](#)).

We have witnessed some studies using RL as the multi-turn conversation strategy by determining model actions such as whether to ask or recommend ([Sun and Zhang, 2018; Lei et al., 2020a, 2020b](#)). However, there is a lot of room for improvement in designing the state, action, and reward in RL. For instance, more sophisticated actions can be taken into consideration such as answering open-domain questions raised by users ([Zhu et al., 2021](#)) or chatting non-task-oriented topics for entertainment purposes ([Wu and Yan, 2018; Liu et al., 2020ab](#)). Besides, more advanced and intuitive RL technologies can be considered to avoid the difficulties, e.g., hard to train and converge, in basic RL models ([Wang et al., 2020a](#)). For example, Inverse RL (IRL) ([Ng and Russell, 2000](#)) can be considered to learn a proper reward function from the observed examples in certain CRS scenarios, where there are too many user behavior patterns so the reward is hard to define. Meta-RL ([DuanJohn Schulman et al., 2016; Wang et al., 2016a](#)) can be adopted in CRSs, where the interaction is sparse and various, to speed up the training process and to improve the learning efficiency for novel subsequent tasks.

7.4. Knowledge enrichment

A natural idea to improve CRSs is to introduce additional knowledge. In early stages of the development of CRSs, only the recommended items themselves were considered (Christakopoulou et al., 2016). Later, the attribute information of items was introduced to assist in modeling user preferences (Christakopoulou et al., 2018). Even more recent studies consider the rich semantic information in knowledge graphs (Zhou et al., 2020a; Lei et al., 2020b; Xu et al., 2020; Moon et al., 2019). For example, to better understand concepts in a sentence such as “I am looking for scary movies similar to *Paranormal Activity* (2007)”, Zhou et al. (2020a) propose to incorporate two external knowledge graphs (KGs): one word-oriented KG providing relations (e.g., synonyms, antonyms, or co-occurrence) between words so as to comprehend the concept “scary” in the sentence; one item-oriented KG carrying structured facts regarding the attributes of items.

Besides knowledge graphs, multimodal data can also be integrated into the original text-based CRSs since it can enrich the interaction from new dimensions. There are some studies that exploit the visual modality, i.e., images, in dialogue systems (Yu et al., 2019b; Liao et al., 2018; Cui et al., 2019; Zhang et al., 2019). For example, Yu et al. (2019b) propose a visual dialogue augmented CRS model. The model will recommend a list of items in photos, and the user will give text-based comments as feedback. The image not only helps the model learn a more informative representation of entities, but also enable the system to better convey information to the user. Except for the visual modality, other modalities can benefit CRSs and could be integrated. For example, spoken natural language can convey users’ emotions as well as sentiments towards certain entities (Pittermann et al., 2010).

7.5. Better Evaluation and user simulation

The evaluation of CRSs still has a long way to go. As we introduced in Section 6.3, evaluating the CRS requires real-time feedback, which is expensive in real-world situations (Jagerman et al., 2019). Thus, most CRSs adopt user simulation techniques to create an environment (Zhang and Balog, 2020). However, simulated users cannot fully replace human beings. How to simulate users with maximum fidelity still needs further research. Feasible directions include designing systematic simulation agenda (Zhang and Balog, 2020; Schatzmann et al., 2007), building dense user interactions for reliable simulation (Zou et al., 2020a; Chen et al., 2019ab; Bai et al., 2019), and modeling user choice behaviors over the slate recommendation (Le et al., 2019; McInerney et al., 2020; Afsar et al., 2021).

In addition, CRSs work on different datasets and they have various assumptions and settings. Therefore, developing comprehensive evaluation metrics and procedures to assess the performance of CRSs remains an open problem. Recently, Zhou et al. (2021) have implemented an open-source CRS toolkit, enabling evaluation between different CRS models. However, their implemented models are mainly based on end-to-end dialogue systems (Li et al., 2018; Chen et al., 2019bb; Zhou et al., 2020a) or deep language models (Zhou et al., 2020c), the models focusing on the explicit conversation strategy (Lei et al., 2020a, 2020b) are absent.

8. Conclusion

Recommender systems are playing increasingly important role in information seeking and retrieval. Despite having been studied for decades, traditional recommender systems estimate user preferences only in a static manner like through historical user behaviours and profiles. It offers no opportunities to communicate with users about their preferences. This inevitably suffers from a fundamental information asymmetry problem: a system will never know precisely what a user likes (especially when his/her preference drifts frequently) and why the user likes an item. The envision of conversational recommender systems

(CRSs) brings a promising solution to such problems. With the interactive ability as well as the natural language-based user interface, CRSs can dynamically get explicit user feedback using natural languages, while increasing user engagement and improving user experience. This bold vision provides great potential for the future of recommender system, hence actively contributes to the development of the next generation of information seeking techniques.

Although the build of CRS is an emerging field, we have spotted great efforts from different perspectives. In this survey, we acknowledge those efforts, with the aim to summarize the existing studies and to provide insightful discussions. We tentatively gave a definition of the CRS and introduced a general framework of CRSs that consists of three components: a user interface, a conversation strategy module and a recommender engine. Based on this decomposition, we distilled five existing research directions, namely: (1) question-based user preference elicitation; (2) multi-turn conversational recommendation strategies; (3) dialogue understanding and generation; (4) exploitation-exploration tradeoffs for cold users; (5) evaluation and user simulation. For each direction, we reviewed the existing efforts and their limitation in one section, leading to the primary structure of this survey. Despite the progresses on the above five directions, more interesting problems remain to be explored in the field of CRSs, such as, (1) joint optimization of three components; (2) bias and debiasing methods in CRSs; (3) multi-turn conversational recommendation strategies; (4) multi-modal knowledge enrichment; (5) evaluation and user simulation. Our discussions above provide a comprehensive retrospect of current progress of CRSs which can serve as the basis for the further development of this field. By providing this survey, we call arm to this emerging and interesting field. We hope this survey can inspire the researchers and practitioners from both industry and academia to push the frontiers of CRSs, making the thoughts and techniques of CRSs more prevalent for the next generation of information seeking techniques.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (61972372, U19A2079) and the National Key Research and Development Program of China (2020YFB1406703, 2020AAA0106000).

All content represents the opinion of the authors, which is not necessarily shared or endorsed by their respective employers and/or sponsors.

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