

IMPERIAL

Department of Mathematics

Deep Reinforcement Learning for Ad Personalization

Martin Batěk

CID: 00951537

Supervised by Mikko Pakkanen

2 September 2024

Submitted in partial fulfilment of the requirements for the
MSc in Machine Learning and Data Science of
Imperial College London

The work contained in this thesis is my own work unless otherwise stated.

Signed: Martin Batěk

Date: 17 July 2024

Abstract

ABSTRACT GOES HERE

Acknowledgements

ANY ACKNOWLEDGEMENTS GO HERE

Contents

1. Introduction	1
2. Background	4
2.1. Deep CTR Prediction	4
2.1.1. Problem Formulation and Ad Marketplace Data	4
2.1.2. Shallow CTR Models	6
2.1.3. Introducing MLP's in CTR prediction	8
2.1.4. Single vs Dual Tower Architectures	9
2.1.5. DNN Enhanced CTR models	10
2.1.6. Feature Interaction Operator Models	15
2.2. Deep Reinforcement Learning	15
2.2.1. Reinforcement Learning Basics: Markov Decision Processes and Dynamic Programming	15
2.2.2. Q-Learning and Deep Q-Learning	15
2.2.3. DRN: Deep Reinforcement Learning for News Recommendation . .	15
3. Deep CTR model Evaluation	17
3.1. Model Selection Methodology	17
3.2. Experiment Setup	17
3.2.1. Datasets and Preprocessing	17
3.2.2. Evaluation Metrics	17
3.2.3. Hyperparameter Selection	17
3.3. Deep CTR Model Results	17
4. Deep Reinforcement Learning for Ad Personalization	18
4.1. DeepCTR-RL Framework	18
4.1.1. Model Framework	18
4.1.2. Feature types	18
4.1.3. Double Deep Q-Learning Network	18
4.1.4. Exploration	18
4.1.5. Experience Replay	18
4.2. Experiment Setup	18
4.2.1. Dataset and Preprocessing	18
4.2.2. Evaluation Metrics	18
4.2.3. Hyperparameter Selection	18
4.3. Deep CTR-RL Results	18
5. Discussion	19

6. Conclusion	20
A. Appendix	A1
A.1. Abbreviations and Acronyms	A1
A.2. Notation	A1

1. Introduction

The global digital advertising market is worth approximately \$602 billion today. Due to the increasing rate of online participation since the COVID-19 pandemic, this number has been rapidly increasing and is expected to reach \$871 billion by the end of 2027 (eMarketer, 2023). Many of the major Ad platforms such as Google, Facebook and Amazon operate on a cost-per-user-engagement pricing model, which usually means that advertisers get charged for every time a user clicks on an advertisement. This means that there is a significant commercial incentive to design Ad-serving platforms that ensure that the content shown to each user is as relevant as possible, so as to maximize user engagement and platform revenues as much as possible.



Figure 1.1.: Global Digital Ad Spending 2021-2027. Image taken from eMarketer (2023)

Attaining accurate Click-Through Rate (CTR) prediction is a necessary first step for Ad personalization, which is why study of CTR prediction methods have been an extremely active part of Machine Learning research over the past through years. Initially, shallow prediction methods such as Logistic Regression, Factorization Machines (Rendle, 2010) and Field-Aware Factorization Machines (Juan et al., 2016) have been used for CTR prediction. However, these methods have often been shown to be unable to capture

the higher order feature interactions in the sparse multi-value categorical Ad Marketplace datasets (Zhang et al., 2021). Since then, Deep Learning methods have been shown to show superior predictive ability on these datasets. A number of Deep Learning models have been proposed, each using a different techniques for feature interaction modelling, ranging from Deep Learning extensions of Factorization Machines such as DeepFM (Guo et al., 2017), to novel methods such as AutoInt (Song et al., 2019). By employing a multi-towered neural network architecture, these models are able to capture both low-order and high-order feature interactions in the data, and therefore tend to achieve superior predictive performance to their shallow counterparts.

However, irrespective of how well these models perform in a static environments, the reality is that user preferences and advertisement characteristics are constantly changing. Like most online recommender systems, Ad personalization models must be able to adapt to these changes in order to continue to provide accurate predictions over the longer period (Zheng et al., 2018). This problem necessitates the use of Reinforcement Learning for Ad personalization.

Reinforcement Learning is a subdomain of Machine Learning in which the goal is for an agent to learn an optimal policy that maximizes the expected reward in an environment where the state-action-reward progression can be modelled as a Markov Decision Process (Puterman, 2014). Early Reinforcement Learning methods involved deriving a the transition probabilities for the state-action pairs on the basis of interactions with the environment and then using Dynamic Programming methods such as the Upper Confidence Bound RL (UCB-RL) algorithm (Auer et al., 2008) and the the Thompson Sampling algorithm for Reinforcement Learning (Pike-Burke, 2024). However, in cases where the state-action space is too sparse to be reasonably enumerated, it is often more practical to user a function approximator to directly estimate the expected cumulative reward for each action in each state. This method of Reinforcement Learning is commonly referred to as Q-learning (Watkins, 1989), and has the advantage of being *model-free*, meaning that it does not require the agent to have a model of the environment thereby making it more scalable to large and sparse datasets. In (Hornik et al., 1989), (Cybenko, 1989) and (Hornik et al., 1990) Deep Neural Networks with activation functions are shown to be universal function approximators which naturally lead to the incorporation of DNN's in Q-Learning. This has lead to the development of the Deep Q-Learning Agent, which has been shown to be able to learn optimal policies in a number of different domains, such as the Atari 2600 game environment Mnih et al. (2015). Beyond this, Deep Reinforcement Learning has shown promising results in a number of different applications, including robot control and computer vision (Wang et al., 2024). In the context of Ad personalization, DRL has also be applied to online recommender systems such as News article recommendation (Zheng et al., 2018) and video recommendation on Youtube (Chen et al., 2019). In both papers, the authors show that the DRL agent is able to learn an optimal content recommendation policy on the basis of user engagement data. This reveals that there is potential for applying these methods to the problem of Ad personalization, thereby creating a truly adaptive marketing platform.

Research Question and Contributions

In this report, I aim to construct a Ad serving system that is truly adaptive and personalized to the changing user preferences and advertisement characteristics. In order to achieve this goal, I will first need to find a suitable Deep Learning Model architecture for CTR prediction, and then incorporating this model as the Q-function approximator in a Deep Q-Learning algorithm. The key contributions that I make in this report are as follows:

- I evaluate the performance of five popular Deep Learning models for CTR prediction on three well-known benchmark datasets, Criteo (Tien et al., 2014), KDD12 (Aden, 2012) and Avazu (Wang and Cukierski, 2014).
- I construct a novel Deep Reinforcement Learning Frame for Ad personalization, and as a proof-of-concept and evaluate its performance using the KDD12 dataset.

Structure of the Report

In chapter 2, I begin by providing a background introducing the problem of Click-Through Rate prediction in the context of Ad personalization, and explore the unique challenges posed by the typically sparse multi-value categorical datasets that are common in the Ad marketplace. I then proceed to review the literature on Deep Learning models for CTR prediction, highlighting the different techniques that each framework uses to capture the key feature interactions in the data. I also review the literature on Deep Reinforcement Learning, specifically the DRN algorithm introduced by Zheng et al. (2018), which can be analogously applied to the Ad personalization context. In chapter 3, I evaluate the performance of different Deep Learning models for CTR prediction on three well-known benchmark datasets, Criteo (Tien et al., 2014), KDD12 (Aden, 2012) and Avazu (Wang and Cukierski, 2014). In chapter 4, I construct a Deep Reinforcement Learning model for Ad personalization and evaluate its performance on the same benchmark datasets. Finally, in chapter 5, I discuss the results of the experiments and provide some concluding remarks.

2. Background

2.1. Deep CTR Prediction

2.1.1. Problem Formulation and Ad Marketplace Data

In their respective surveys on the use of Deep Learning methods for CTR prediction, Gu (2021) and Zhang et al. (2021) outline the problem of CTR prediction as one that essentially boils down to a binary (click/no-click) classification problem utilizing user/ad-view event level online session records. The goal of CTR prediction is to train a function f that takes in a set of ad marketplace features $\mathbf{x} \in \mathbb{R}^n$, and maps these to a probability that the user will click on the ad in that given context. In other words, $f_{\Theta} : \mathbb{R}^n \rightarrow \mathbb{R}$ such that:

$$\mathbb{P}(\text{click}|\mathbf{x}) = \mathbb{P}(y = 1|\mathbf{x}) = \sigma(f_{\Theta}(\mathbf{x})) \quad (2.1)$$

where y is the binary click label, Θ represents the parameter vector for f and $\sigma(x) = (1 + e^{-x})^{-1}$ is the sigmoid function. To ease the notation for the rest of the report, we will use the shorthand $p(y) = \mathbb{P}(y = 1|\mathbf{x})$ formulations in the following sections.

An instance of the ad marketplace features \mathbf{x} is typically recorded at a user/ad impression event level and typically consists of

- **User Features:** Features that describe the user, such as User ID, demographic information, metrics related to the user’s past interactions with the platform, etc.
- **Ad Features:** Features that describe the ad, such as Ad ID, Advertiser ID and Ad Category.
- **Contextual Features:** Features that describe the context in which the ad is being shown, such as the time of day, the position of the ad on the page and the site on which the ad is being shown.

Figure 2.1 shows a snapshot of the KDD12 dataset, which is a typical example of the type of data that is used for CTR prediction.

A defining characteristic for this type of data is that many of the features are multi-value categories with a high degree of cardinality (He and Chua, 2017). In order to use categorical data in a classifier model, it is common practice to embed these categorical features as multidimensional vectors. While the dimensionality of these embeddings can vary amongst the different sparse categorical features, for the sake of simplicity of notation, below we assume that all sparse categorical feature embeddings have the same dimensionality, D . Let \mathbf{x}_i^{OH} be the one-hot encoded vector representation of the

Click	Impression	DisplayURL	AdID	AdvertiserID	Depth	Position	QueryID	KeywordID	TitleID	DescriptionID	UserID
0	1	4.29812E+18	7686695	385	3	3	1601	5521	7709	576	490234
0	1	4.86057E+18	21560664	37484	2	2	2255103	317	48989	44771	490234
0	1	9.70432E+18	21748480	36759	3	3	4532751	60721	685038	29681	490234
0	1	1.36776E+19	3517124	23778	3	1	1601	2155	1207	1422	490234
0	1	3.28476E+18	20758093	34535	1	1	4532751	77819	266618	222223	490234
0	1	1.01964E+19	21375650	36832	2	1	4688625	202465	457316	429545	490234
0	1	4.20308E+18	4427028	28647	3	1	4532751	720719	3402221	2663964	490234
0	1	4.20308E+18	4428493	28647	2	2	13171922	1493	11658	5668	490234
0	1	5.85475E+17	20945590	35083	2	1	35143	28111	151695	128782	490234
0	1	9.68455E+18	21406020	36943	2	2	4688625	202465	1172072	973354	490234
Target		Ad Features			User Features			Contextual Features			

Figure 2.1.: Snapshot of the KDD12 dataset Aden (2012)

categorical feature x_i . Then the *embedded* feature vector \mathbf{e}_i for categorical feature x_i is given by:

$$\begin{aligned}
\mathbf{e}_i &= \mathbf{B}_i \mathbf{x}_i^{OH} \\
&= [\mathbf{b}_{1,1}^i, \dots, \mathbf{b}_{m_i,1}^i] \mathbf{x}_i^{OH} \\
&= \begin{bmatrix} b_{1,1}^i & \cdots & b_{1,C_i}^i \\ \vdots & \ddots & \vdots \\ b_{D,1}^i & \cdots & b_{D,C_i}^i \end{bmatrix} \begin{bmatrix} 0 \\ \vdots \\ 1 \\ 0 \\ \vdots \end{bmatrix}
\end{aligned} \tag{2.2}$$

where \mathbf{B}_i is the embedding matrix for feature x_i , whose dimensions are determined by the chosen embedding dimension D and the cardinality of the feature, C_i . Assuming that value of x_i is equal to the k -th value in the one-hot encoding mapping, and that therefore the k -th value in \mathbf{x}_i^{OH} is equal to one, Equation 2.2 then simplifies to

$$\mathbf{e}_i = [e_{i1}, \dots, e_{iD}]^\top = [b_{1k}^i, b_{2k}^i, \dots, b_{Dk}^i]^\top = \mathbf{b}_k^i \tag{2.3}$$

which is the k -th column of the embedding matrix \mathbf{B}_i , otherwise referred to as the k -th embedding vector (Hancock and Khoshgoftaar, 2020). The processed data $\tilde{\mathbf{x}}$ that then gets fed into the model is then composed of a concatenation of all sparse feature embeddigs \mathbf{e}_i and standardized dense numerical feature values $z_i = (x_i - \bar{x}_i) / \sqrt{\text{Var}(x_i)}$:

$$\begin{aligned}
\tilde{\mathbf{x}} &= [\mathbf{e}_1^\top, \dots, \mathbf{e}_s^\top, z_{s+1}, \dots, z_{s+d}] \\
&= [e_{1,1}, \dots, e_{1,D}, e_{2,1}, \dots, e_{s,D}, z_{s+1}, \dots, z_{s+d}] \\
&= [\tilde{x}_1, \dots, \tilde{x}_{\tilde{n}}]
\end{aligned} \tag{2.4}$$

where s and d are the number of *sparse* categorical features and *dense* numerical features respectively in \mathbf{x} , and $\tilde{n} = D \cdot s + d$ is the resulting dimensionality of $\tilde{\mathbf{x}}$. Again, to ease the notation in the remainder of the report, we will assume that the preprocessing steps described above are applied to the data, and all formulaic expressions of the models

in the following section will be expressed in terms of $\tilde{\mathbf{x}} = \{\tilde{x}_j\}_{j=1}^{\tilde{n}}$.

The problem posed by high cardinality is that when m_i is large, the high sparsity of the one-hot encoded vector x_i^{OH} can make it extremely difficult for a model to learn the key *implicit* features and patterns present in the data (Gu, 2021). This is indeed the key challenge in building an accurate CTR prediction model, and is a key motivating factor as to why Deep Neural networks have outperformed the classical shallow counterparts. This transition will be examined in more detail in the following section.

2.1.2. Shallow CTR Models

??

Logistic Regression

The earliest examples of CTR classification models incorporated classical “shallow” (single layer) statistical regression methods. The most basic example of this was the **Logistic Regression** model, as implemented by Richardson et al. (2007) on advertisement data from the Microsoft Search engine. The LR model is composed by modelling the *log-odds* (also referred to as the *logit*) of a positive binary label as a linear combination of all of the respective feature values:

$$f_{\Theta}^{LR}(\tilde{\mathbf{x}}) = \theta_0 + \sum_{j=1}^{\tilde{n}} \theta_j \tilde{x}_j \quad (2.5)$$

where $f_{\Theta}^{LR} : \mathbb{R}^n \rightarrow \mathbb{R}$ represents the Logistic regression model parametrized by $\Theta = (\theta_0, \dots, \theta_{\tilde{n}})$. The benefits of the LR model are that due to its simplicity and low number of parameters, it is relatively easy to train in computational terms and also relatively easy to deploy (Zhang et al., 2021). However, the formulation in equation 2.5 reveals that the LR model does not explicitly account for *feature interactions*. As outlined in section 2.1.1, the categorical features tend to have a high cardinality, resulting in highly sparse feature embeddings. Many of the important patterns for CTR prediction are therefore likely to be expressed in terms of *combinations of features* rather than the individual feature values themselves. For example, a user’s tendency to click on a given advertisement is likely to be influenced by the *combination* of the category of good or service the given advertisement is trying to sell (e.g. premium fashion retail, travel, electronics et. cetera) and the demographic/socio-economic category that the given user falls into (e.g. university student, young professional, retiree). These feature combinations (and the corresponding combination of respective field values in the preprocessed feature vector $\tilde{\mathbf{x}}$) are commonly referred to in the literature as *cross-features* (Zhang and Zhang, 2023) or more commonly *feature interactions* (Cheng et al., 2016; Song et al., 2019; Xiao et al., 2017).

Whilst it is possible to incorporate feature interactions in an LR model through feature engineering, this quickly becomes infeasible for large sparse datasets. A number of techniques have been developed to automate the necessary feature engineering steps

for this, either by implicitly assigning a weight to all second order feature interactions (Chang et al., 2010) or by utilizing Gradient Boosted Decision Trees to pick out the key interactions (Cheng et al., 2014). Unfortunately, the prior still tends to exhibit poor performance with sparse data, whereas the fact that the Gradient Boosting algorithm for the latter is difficult to parallelize makes this solution difficult to scale in many applications in practice (Zhang et al., 2021).

Factorization Machines

Factorization Machines first proposed by Rendle (2010) can be thought of as an extension of the Logistic Regression framework in equation 2.5 with additional terms that explicitly account for the interactions between different features. Its relative simplicity and computational scalability has made it a widely popular framework for CTR modelling (Gu, 2021). A 2-way (maximum feature interaction degree of 2) Factorization Machine model is formulated as:

$$f_{\Theta}^{FM^2}(\tilde{\mathbf{x}}) = \theta_0 + \sum_{j=1}^{\tilde{n}} \theta_j \tilde{x}_j + \sum_{j=1}^{\tilde{n}} \sum_{k=j+1}^{\tilde{n}} \langle \mathbf{v}_j, \mathbf{v}_k \rangle \tilde{x}_j \tilde{x}_k \quad (2.6)$$

where $\langle \cdot, \cdot \rangle$ represents the inner product between two vectors, the final interaction term above is parametrized by $\mathbf{V} \in \mathbb{R}^{\tilde{n} \times F}$. Each row \mathbf{v}_j of \mathbf{V} represents the j -th feature in $\tilde{\mathbf{x}}$ in terms of F latent factors. The factorization matrix \mathbf{V} is typically fitted by optimizing the binary cross-entropy loss function by means of Stochastic Gradient Descent. It is intuitive to see that \mathbf{V} will be fitted such that if the interaction between feature j and k have a positive impact on $p(y)$, then j -th and k -th rows of \mathbf{V} will have positive inner products (and vice versa) (Zhang et al., 2021).

Rendle (2010) shows that although direct evaluation of equation 2.6 would appear to have a complexity of $O(F\tilde{n}^2)$, the 2-way FM model in fact scales linearly in \tilde{n} and F :

Lemma 2.1.1. The model equation of a 2-way factorization machine (eq. 2.6) can be computed in linear time $O(L\tilde{n})$.

Proof.

Due to the factorization of the pairwise interactions, there is no model parameter that directly depends on two features (j, k) . This means that pairwise interactions can be reformulated as such

$$\begin{aligned}
& \sum_{j=1}^{\tilde{n}} \sum_{k=j+1}^{\tilde{n}} \langle \mathbf{v}_j, \mathbf{v}_k \rangle \tilde{x}_j \tilde{x}_k \\
&= \sum_{j=1}^{\tilde{n}} \sum_{k=j+1}^{\tilde{n}} \sum_{f=1}^F v_{j,f} v_{k,f} \tilde{x}_j \tilde{x}_k \\
&= \frac{1}{2} \left(\sum_{j=1}^{\tilde{n}} \sum_{k=1}^{\tilde{n}} \sum_{f=1}^F v_{j,f} v_{k,f} \tilde{x}_j \tilde{x}_k - \sum_{j=1}^{\tilde{n}} \sum_{f=1}^F v_{j,f} v_{j,f} \tilde{x}_j \tilde{x}_j \right) \\
&= \frac{1}{2} \sum_{f=1}^F \left(\sum_{j=1}^{\tilde{n}} v_{j,f} \tilde{x}_j \sum_{k=1}^{\tilde{n}} v_{k,f} \tilde{x}_k - \sum_{j=1}^{\tilde{n}} v_{j,f}^2 \tilde{x}_j^2 \right) \\
&= \frac{1}{2} \sum_{f=1}^F \left(\left(\sum_{j=1}^{\tilde{n}} v_{j,f} \tilde{x}_j \right)^2 - \sum_{j=1}^{\tilde{n}} v_{j,f}^2 \tilde{x}_j^2 \right)
\end{aligned}$$

The complexity of the final line above is $O(L\tilde{n})$, and hence the FM formulation as per equation 2.6 scales linearly in L and \tilde{n} . \square

This quality greatly simplifies the computational complexity of scaling the FM model to larger datasets with a more sparse categorical features. Moreover, the Factorization Machine framework can be generalized to degree R (i.e. up to any limit of feature interaction order) as follows:

$$f_{\Theta}^{FM^R} = \theta_0 + \sum_{j=1}^{\tilde{n}} \theta_j \tilde{x}_j + \sum_{r=1}^R \sum_{j_1=1}^{\tilde{n}} \cdots \sum_{j_r=j_{r-1}+1}^{\tilde{n}} \left(\prod_{k=1}^r \tilde{x}_{j_k} \right) \left(\sum_{f=1}^{F_r} \prod_{k=1}^r v_{j_k,f}^{(r)} \right) \quad (2.7)$$

The FM framework therefore provides an intuitive and computationally scalable method to account for key feature interactions without the need of extensive feature engineering. Extensions and improvements to FM have been proposed, most notably in the form of the Field-Aware Factorization Machine (FFM) framework by Juan et al. (2016), which only accounts for interactions between features of different fields (in otherwords, it ignores the interaction between \tilde{x}_j and \tilde{x}_k if both are components of embedding vector embed_i for some categorical feature x_i) as well as Gradient Boosted Factorization Machines (Cheng et al., 2014), which again aims to augment the FM framework by means of the Gradient Boosting algorithm.

2.1.3. Introducing MLP's in CTR prediction

Despite the advantages of the FM framework, a setback of the formulation in equation 2.7 is that the framework grows highly complex and overparametrized for higher values of R . As a consequence, only the 2-way FM framework as per equation 2.6 tends to

be implemented in practice, meaning that in FM alone is practically insufficient for capturing feature interactions of order $\gg 2$ (Guo et al., 2017). Deep Neural Networks present a powerful alternative for addressing this shortcoming. Neural networks benefit from being universal function approximators (Cybenko, 1989) and from the fact that neural network batch training is paralelizabile by means of GPU accelerated computation. This has lead to the successfull application of Deep Learning algorithms across multiple fields such as Natural Language Processing and Image classification (He et al., 2016; Krizhevsky et al., 2017; LeCun et al., 1998). These factors and successes showed that DNN's have the potential to extract informative feature representations from highly sparse and abstract data, and as a consequence, the application of DNN's in CTR prediction started recieving attention in the mid-2010's.

The **Multilayer Perceptron** (MLP) is the most elementary type of Deep Neural Network (Webster, 2024). In general, a MLP with L hidden layers is formulated as such:

$$\mathbf{h}^{(0)} := \tilde{\mathbf{x}} \quad (2.8)$$

$$\mathbf{h}^{(l)} = \phi_l \left(\mathbf{W}^{(l-1)} \mathbf{h}^{(l-1)} + \mathbf{b}^{(l-1)} \right), l = 1, \dots, L \quad (2.9)$$

$$\hat{y} = \phi_{out} \left(\mathbf{w}^{(L)} \mathbf{h}^{(L)} + b^{(L)} \right) \quad (2.10)$$

where $\mathbf{W}^{(k)} \in \mathbb{R}^{n_{l+1} \times n_l}$, $\mathbf{b}^{(k)} \in \mathbb{R}^{n_{l+1}}$, $\mathbf{h}^{(l)} \in \mathbb{R}^{n_l}$, $n_0 = \tilde{n}$, n_l is the number of hidden units in layer l and ϕ_l is the activation function for layer l , When rearranged in the form of equation 2.1, the above becomes:

$$f_{\Theta}^{MLP}(\tilde{\mathbf{x}}) = \psi_{out}(\psi_L(\dots \psi_1(\tilde{\mathbf{x}})\dots)) \quad (2.11)$$

where each function ψ_l represents the affine transformation and element-wise activation operation for layer l . MLPs can be thought of as an acyclic graph, as displayed in Figure 2.2. The data $\tilde{\mathbf{x}}$ first gets fed through the *input layer*, then gets processed by multiple *hidden layers* that include a series of affine transfromations followed by activation functions, before the final result is produced by the *output layer*.

Figure 2.2 demonstrates the potential that DNN's have for modelling higher order feature interactions. By training the network by means of Stochastic Gradient Descent, it should be possible to calculate the appropriate weight (\mathbf{W}_l) and bias (\mathbf{b}_l) parameters in order capture the relevant high-order feature patterns in the data. As such, many CTR modelling frameworks have been developed that use Deep Learning techniques to build upon and improved the previously discussed classical methods by incorporating Deep Neural Networks such as the ML in the model architecture (Zhang et al., 2021).

2.1.4. Single vs Dual Tower Architectures

Before moving on to DNN enhanced CTR models in section 2.1.5 it is worth briefly discussing the difference between **Single-Tower** models and **Dual-Tower** architecture models. Single Towel models place all layers successively in the architecture, and can



Figure 2.2.: Multilayer Perceptron with two hidden layer. Taken from (Webster, 2024)

generally be formulated as in equation 2.11. Since all feature inputs are passed through the same set of successive affine transformations and activations, Single Tower models are usually able to capture higher order feature interactions, but the signal from the low-order interactions tend to be lost (Zhang et al., 2021). The FNN (Zhang et al., 2016), FGCNN (Liu et al., 2019) and PNN (Qu et al., 2016) models covered in the subsections 2.1.5 and 2.1.6 are examples of Single Tower models.

In order to avoid diluting the signal from the lower order feature interactions, many architectures adopt a Dual Tower architecture, as shown on the right-hand side of Figure 2.3. A separate **Feature Interaction Layer** is placed parallelly to the DNN, and the final output is composed of a weighted sum of the feature interaction and DNN outputs. With this architecture, the feature interaction layer is usually dedicated to capturing the important lower order feature interaction signals, whereas the DNN acts as a *residual network* for capturing any meaningful signals that may be missing. As a result, Dual Tower networks tend to benefit from better training stability and better performance (Zhang et al., 2021).

2.1.5. DNN Enhanced CTR models

Factorization-machine Supported Neural Networks

One of the earliest example of the use of Deep Neural Networks being used to enhance existing CTR modeling methods is the **Factorization-machine Supported Neural Network** (FNN) (Zhang et al., 2016). The FNN model is a Single Tower model that works by pretraining a 2-way Factorization Machine model as in equation 2.6 on the concatenated one-hot encoded categorical feature vectors, and then using the feature interaction vectors and weights as the embedding matrix.

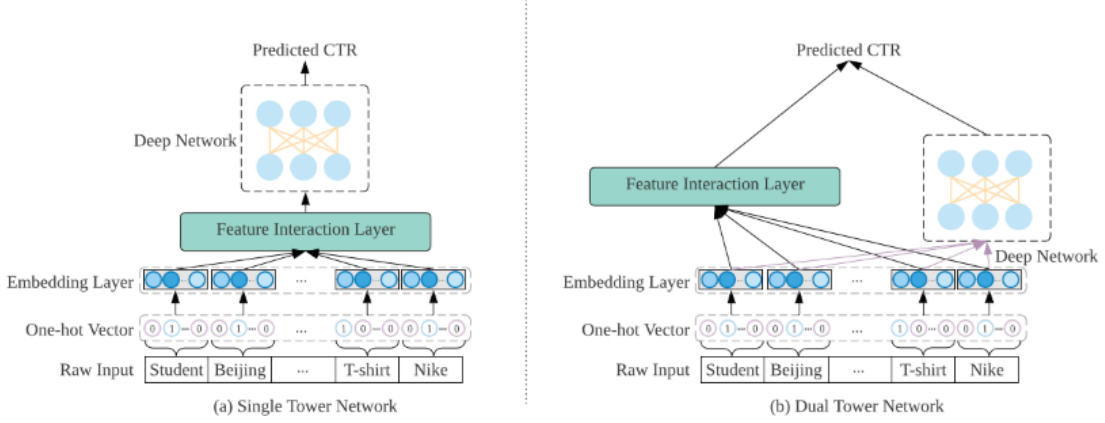


Figure 2.3.: Single vs Dual Architecture Networks. Source: (Zhang et al., 2021)

Below we start with the concatenated one-hot encoded categorical feature vector:

$$\dot{\mathbf{x}} = [\mathbf{x}_1^{OH}, \dots, \mathbf{x}_n^{OH}]$$

$$f_{\Theta}^{FM^2} = \theta_0 + \sum_{j=1}^{\hat{n}} \theta_j \dot{x}_j + \sum_{j=1}^{\hat{n}} \sum_{k=j+1}^{\hat{n}} \langle \mathbf{v}_j, \mathbf{v}_k \rangle \dot{x}_j \dot{x}_k$$

Using the weights and biases from $\Theta = (\theta_0, \theta_1, \dots, \theta_{\hat{n}}, \mathbf{v}_1, \dots, \mathbf{v}_{\hat{n}})$, the preprocessed MLP input is calculated as follows:

$$\tilde{\mathbf{x}} = [\theta_0, \mathbf{e}_1^T, \mathbf{e}_2^T, \dots, \mathbf{e}_s^T]$$

where each embedding vector \mathbf{e}_i is defined as the concatenation of the weight (θ_i) and FM interaction vector (\mathbf{v}_i) corresponding to feature i in $\dot{\mathbf{x}}$:

$$\mathbf{e}_i = [\theta_i, \mathbf{v}_i^T]$$

The above can alternatively also be recovered from equation 2.2 by setting the embedding matrix \mathbf{B}_i to a $(F+1) \times C_i$ matrix with the following values

$$\mathbf{B}_i = \begin{bmatrix} b_{1,1}^i & \cdots & b_{1,C_i}^i \\ \vdots & \ddots & \vdots \\ b_{F+1,1}^i & \cdots & b_{F+1,C_i}^i \end{bmatrix} = \begin{bmatrix} \theta_i & \cdots & \theta_i \\ v_1^1 & \cdots & v_{C_i}^1 \\ \vdots & \ddots & \vdots \\ v_1^F & \cdots & v_{C_i}^F \end{bmatrix}$$

Figure 2.4 portrays the structure of this model as it was presented in the original paper by Zhang et al. (2016).

By incorporating the FM model feature interaction vectors in the embedding layer before the DNN, the FNN model is about to leverage the FM model's strength in interaction identification. Simultaneously, the FNN model leverages an MLP network to

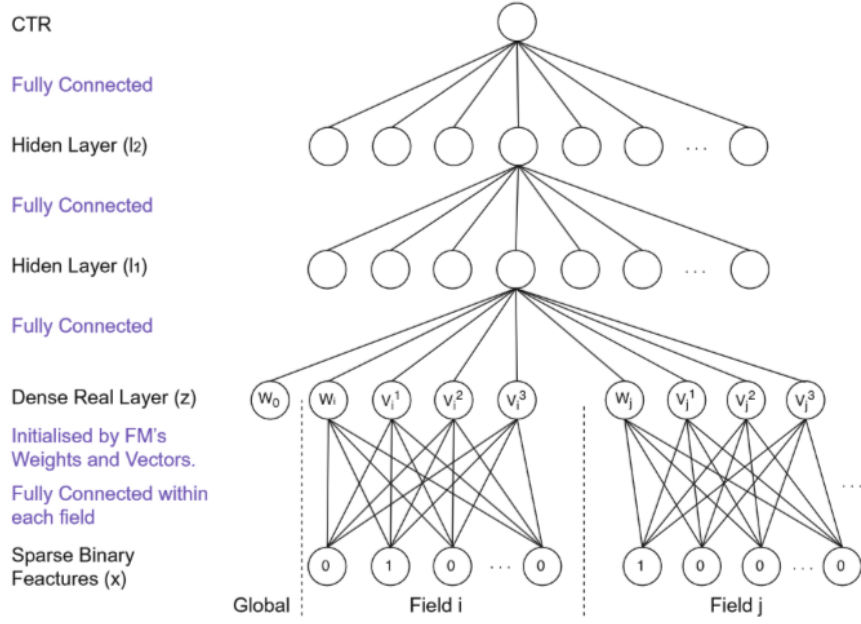


Figure 2.4.: FNN model architecture. Source: (Zhang et al., 2016)

capture the higher order interaction signals much more efficiently than would have been feasibly possible when relying only on FM. Because of this, comprehensive experiments carried out by Zhang et al. (2016) confirmed that FNN has superior CTR estimation performance than both LR and FM.

However Guo et al. (2017) and Zhang et al. (2021) find that due to its Single Tower architecture, lower-order feature interaction signals tend to be lost in the network. Guo et al. (2017) further found that the FM pretraining step described above represents a significant overhead in terms of training efficiency. In the next subsections, we will see how the Wide & Deep and DeepFM models look to solve for these issues.

Wide and Deep

The so-called **Wide and Deep** (W&D) model was developed by Cheng et al. (2016):

$$f_{\Theta}^{W\&D} = \theta_0 + \sum_{k=1}^{\hat{n}} \theta_k \hat{\mathbf{x}}_k + f_{\Phi}^{MLP}(\tilde{\mathbf{x}}) \quad (2.12)$$

Figure 2.5 reveals that the W&D model is composed with a Dual-Tower Architecture, with a Deep Component and a Wide Component (shown on the left and right hand sides of Figure 2.5 respectively). The Deep Component is composed of a MLP with multiple hidden layers, each with the Rectified Linear Unit (ReLU) activation function. The Wide Component is formulated by the first two terms in equation 2.12, and is composed of a simple linear transformation of the input features. The key aspect of the Wide

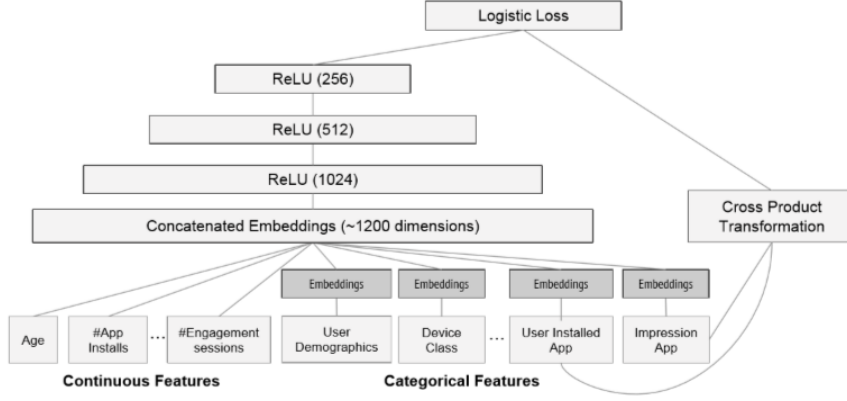


Figure 2.5.: Wide and Deep Model, as illustrated in (Shen, 2017)

Component to take note of is that the linear transformation is not simply applied to the preprocessed features \tilde{x} , but instead to these concatenated with a set of cross-product transformed features. In other words:

$$\hat{\mathbf{x}} = [\tilde{\mathbf{x}}, v_1(\tilde{\mathbf{x}}), \dots, v_P(\tilde{\mathbf{x}})] \quad (2.13)$$

Where $v_k(\tilde{\mathbf{x}}) = \prod_{j=1}^{\tilde{n}} \tilde{x}_j^{c_{kj}}$ and $c_{kj} \in \{0, 1\}$.

Consequently of equation 2.13, the Wide Component *memorizes* the key feature interactions that are defined by the specific *cross-product transformations* ($v_k(\tilde{\mathbf{x}})$) (Cheng et al., 2016). Meanwhile, the Deep Component captures any residual signals that may not have been explicitly included in the manually defined cross-product transformations (Zhang et al., 2021). In this sense, the W&D model overcomes the shortcomings of the FNN model, by having dedicated pathways in the architecture for higher and lower order feature interactions. However, the downside of W&D is the fact that the feature interactions in the Wide component need to be manually incorporated by defining the cross-product transformation functions $\{v_k(x)\}_{k=1}^P$. This means that there is a significant feature engineering component that would be necessary for this model.

DeepFM

The **DeepFM** model was developed by Guo et al. (2017) in order to address the shortcomings of the FNN and W&D models mentioned in this section, as well as those of the PNN model which will be covered in section 2.1.6. Similarly to the W&D model, the DeepFM network two components arranged as a Dual Tower architecture, as visualized in Figure 2.6.

The *FM component* effectively replaces the Wide component in the W&D model. It consists of a 2-way Factorization Machine layer that models pairwise feature interactions between the different fields of $\tilde{\mathbf{x}}$ as inner products of the respective feature latent vectors \mathbf{v}_j (Guo et al., 2017). Due to the linear scalability of the FM discussed in section ??,

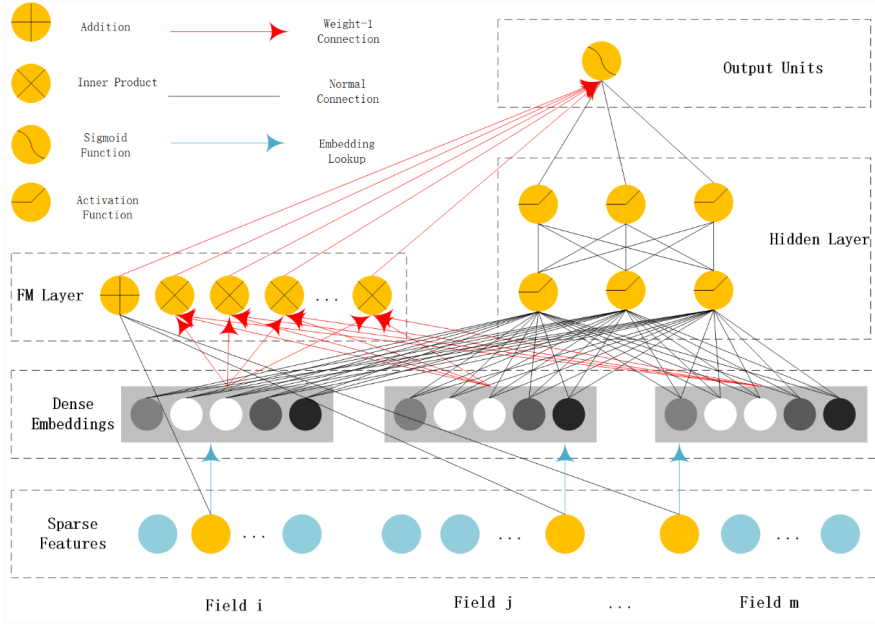


Figure 2.6.: DeepFM network architecture. Source: (Shen, 2017)

the FM component can effectively capture important order-2 feature interactions automatically, without the need to manually define cross-product functions as in the case of the W&D model.

Meanwhile, the *Deep component* fulfills a similar purpose as in the case of the W&D model. The deep component is a MLP network that takes the feature embedding vector $\tilde{\mathbf{x}}$ as inputs, and learns the higher-order feature interactions that cannot be captured by the 2-way FM component. Like with the W&D model, the Deep component acts as a residual network for capturing signals that were omitted by the FM component. The DeepFM model can therefore be formulated as in equation 2.14.

$$f_{\Theta}^{DeepFM} = f_{\Phi}^{FM^2}(\tilde{\mathbf{x}}) + f_{\Omega}^{MLP}(\tilde{\mathbf{x}}) \quad (2.14)$$

A notable difference in the Deep components between the W&D and DeepFM models is in the construction of the embedding layers that preprocess the input to the MLP. In DeepFM, the latent feature vectors (\mathbf{V}) are trainable network weights that are derived during SGD optimization in the FM component. For every successive step in the model training, the learned latent feature vectors are used in the embedding layer that preprocesses that raw input features before the MLP of the Deep component (see Figure 2.7). This is similar to how the feature embeddings were derived in the FNN model (Zhang et al., 2016), except for the fact the FM layer is included in the overall learning architecture of the model. This eliminates the need to pretrain the FM model, thereby allowing for the FM latent feature vectors to be learned concurrently during the overall DeepFM model training procedure (Guo et al., 2017).

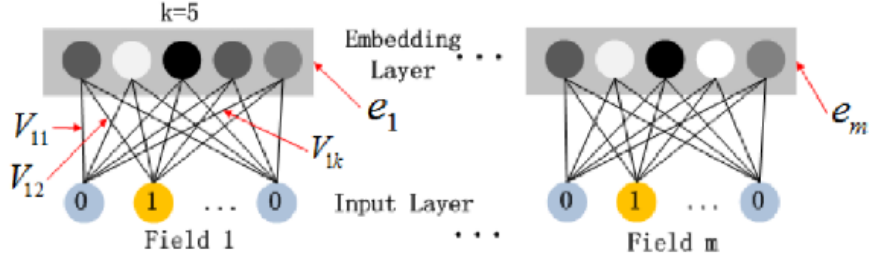


Figure 2.7.: The embedding layer of the Deep Component in the DeepFM model. Source: (Guo et al., 2017)

The key benefits of the DeepFM model are threefold. Firstly, we have already mentioned above that the fact that the FM model is incorporated directly into the model architecture eliminates the need to pretrain the FM latent feature vectors, thereby eliminating the computational overhead that is necessary for this in the case of FNN (Zhang et al., 2016). Secondly, the Dual Tower architecture allows the model to simultaneously learn both low as well as high order feature interactions. Thirdly, the previously discussed computational efficiency of the FM model means that DeepFM is relatively scalable in terms of the number of features and the size of the latent embedding space, especially in comparison to the Product based Neural Network (PNN) models (Qu et al., 2016), which will be covered in section 2.1.6.

2.1.6. Feature Interaction Operator Models

Product Operators - Product Based Neural Network

Convolutional Operators - Feature Generation Convolutional Neural Network

Attention Operators - AutoInt

2.2. Deep Reinforcement Learning

2.2.1. Reinforcement Learning Basics: Markov Decision Processes and Dynamic Programming

2.2.2. Q-Learning and Deep Q-Learning

2.2.3. DRN: Deep Reinforcement Learning for News Recommendation

In their survey, (Wang et al., 2024) describe how deep reinforcement learning combines the aforementioned feature extraction capabilities of DNN's with the decision-making capability of reinforcement learning, which aims to learn an optimal state-action policy which maximizes the expected reward gained in a given environment. In the context of recommendation systems, a significant amount of research has been dedicated to formulating the recommendation problem as a Contextual Multi-Armed Bandit (MAB)

problem setting, where the context consists of user, site and item features (Bouneffouf et al., 2012; Li et al., 2010; Zeng et al., 2016). However, a shortcoming for the MAB approach is that it does not explicitly model the future expected reward for the policy, which may be detrimental in the longer term (Zheng et al., 2018). Markov Decision Process (MDP) models solve for this issue by modelling the state-action progression as a Markov Process, allowing for the stochastic valuation of the future potential rewards for a given recommendation policy (Lu and Yang, 2016; Mahmood and Ricci, 2007). DRN (Zheng et al., 2018) is a MDP framework that leverages a Deep Neural Network to approximate the expected total user response for each recommendation at each state. The two major advantages of DRN are firstly that it is composed on the basis of a continuous state and action representation, meaning that it can be scaled to large and sparse datasets, and secondly that the proposed reward function consists of both the immediate reward (user click) as well as the future expected reward (long term user engagement), thereby allowing for better recommendations over a user’s lifetime.

3. Deep CTR model Evaluation

3.1. Model Selection Methodology

As explained above, I will explore a number of deep learning models. I selected five popular models on the basis of the following criteria

- Competitive prediction accuracy in the KDD12, Criteo and Avazu datasets as published on Papers with Code.
- Ideally, I was looking for a representative set of models for each model type as discussed in (Zhang et. al. 2021). Therefore I was looking for models that employed Product Interaction Operators, Attention Operators and Factorization Machines as a basis.
- The code for the model has to be accessible and intuitive to use.

On the basis of the above criteria, I have chosen the following models to explore:

- Factorization Supported Neural Networks
- Product Based Neural Networks
- Wide and Deep
- DeepFM
- Automatic Feature Interaction (AutoInt)

3.2. Experiment Setup

3.2.1. Datasets and Preprocessing

3.2.2. Evaluation Metrics

3.2.3. Hyperparameter Selection

3.3. Deep CTR Model Results

4. Deep Reinforcement Learning for Ad Personalization

4.1. DeepCTR-RL Framework

4.1.1. Model Framework

4.1.2. Feature types

4.1.3. Double Deep Q-Learning Network

4.1.4. Exploration

4.1.5. Experience Replay

4.2. Experiment Setup

4.2.1. Dataset and Preprocessing

4.2.2. Evaluation Metrics

4.2.3. Hyperparameter Selection

4.3. Deep CTR-RL Results

5. Discussion

Discussion goes here.

6. Conclusion

Conclusion goes here.

A. Appendix

A.1. Abbreviations and Acronyms

Term	Definition	Reference
LR	Logistic Regression	2.1.3
FM	Factorization Machine	
FFM	Field-Aware Factorization Machine	
DNN	Deep Neural Network	
MLP	Multilayer Perceptron	

A.2. Notation

Symbol	Definition	Reference
\mathbf{x}	Feature vector, before pre-processing	
n	the number of features in \mathbf{x}	
x_i	The i -th feature in \mathbf{x}	
\mathbf{x}_i^{OH}	One-hot encoded vector representation of categorical feature i	
\mathbf{e}_i	Embedded vector representation of categorical feature i	
z_i	Mean and variance standardized value for feature i from \mathbf{x}	
$\tilde{\mathbf{x}}$	\mathbf{x} after categorical embedding and numerical standardization.	
f	Pre-sigmoid classification function	
Θ	Parameter vector for f	

Bibliography

- Yi Wang Aden. Kdd cup 2012, track 2, 2012. URL <https://kaggle.com/competitions/kddcup2012-track2>.
- Peter Auer, Thomas Jaksch, and Ronald Ortner. Near-optimal regret bounds for reinforcement learning. In *Advances in Neural Information Processing Systems*. Curran Associates, Inc., 2008.
- Djallel Bouneffouf, Amel Bouzeghoub, and Alda Lopes Gancarski. A contextual-bandit algorithm for mobile context-aware recommender system. In Tingwen Huang, Zhigang Zeng, Chu Li, ong, and Chi Sing Leung, editors, *Neural Information Processing*, pages 324–331, Berlin, Heidelberg, 2012. Springer Berlin Heidelberg. ISBN 978-3-642-34487-9.
- Yin-Wen Chang, Cho-Jui Hsieh, Kai-Wei Chang, Michael Ringgaard, and Chih-Jen Lin. Training and testing low-degree polynomial data mappings via linear svm. *Journal of Machine Learning Research*, 11(4), 2010.
- Minmin Chen, Alex Beutel, Paul Covington, Sagar Jain, Francois Belletti, and Ed H. Chi. Top-k off-policy correction for a reinforce recommender system. In *Proceedings of the Twelfth ACM International Conference on Web Search and Data Mining*, WSDM '19, page 456–464, New York, NY, USA, 2019. Association for Computing Machinery. ISBN 9781450359405. doi: 10.1145/3289600.3290999. URL <https://doi.org/10.1145/3289600.3290999>.
- Chen Cheng, Fen Xia, Tong Zhang, Irwin King, and Michael R. Lyu. Gradient boosting factorization machines. In *Proceedings of the 8th ACM Conference on Recommender systems*, page 265–272, 2014.
- Heng-Tze Cheng, Levent Koc, Jeremiah Harmsen, Tal Shaked, Tushar Chandra, Hrishi Aradhye, Glen Anderson, Greg Corrado, Wei Chai, Mustafa Ispir, Rohan Anil, Zakaria Haque, Lichan Hong, Vihan Jain, Xiaobing Liu, and Hemal Shah. Wide & deep learning for recommender systems. In *Proceedings of the 1st Workshop on Deep Learning for Recommender Systems*, DLRS 2016, page 7–10, New York, NY, USA, 2016. Association for Computing Machinery. ISBN 9781450347952. doi: 10.1145/2988450.2988454. URL <https://doi.org/10.1145/2988450.2988454>.
- G. Cybenko. Approximation by superpositions of a sigmoidal function. *Mathematics of control, signals, and systems*, 2(4):303–314, 1989. doi: 10.1007/BF02551274.

- eMarketer. Digital advertising spending worldwide from 2021 to 2027 (in billion u.s. dollars). Technical report, Statista Inc., 2023. URL <https://www-statista-com.iclibezp1.cc.ic.ac.uk/statistics/237974/online-advertising-spending>.
- Liqiong Gu. Ad click-through rate prediction: A survey. In Christian S. Jensen, Ee-Peng Lim, De-Nian Yang, Chia-Hui Chang, Jianliang Xu, Wen-Chih Peng, Jen-Wei Huang, and Chih-Ya Shen, editors, *Database Systems for Advanced Applications. DASFAA 2021 International Workshops*, pages 140–153, Cham, 2021. Springer International Publishing. ISBN 978-3-030-73216-5.
- Huifeng Guo, Ruiming Tang, Yunming Ye, Zhenguo Li, and Xiuqiang He. Deepfm: A factorization-machine based neural network for ctr prediction. *CoRR*, abs/1703.04247, 2017. URL <http://arxiv.org/abs/1703.04247>. 1703.04247.
- John T. Hancock and Taghi M. Khoshgoftaar. Survey on categorical data for neural networks. *Journal of Big Data*, 7(1):28, 2020. doi: 10.1186/s40537-020-00305-w. URL <https://doi.org/10.1186/s40537-020-00305-w>. ID: Hancock2020.
- Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, page 770–778, 2016.
- Xiangnan He and Tat-Seng Chua. Neural factorization machines for sparse predictive analytics, -08-16 2017.
- Kurt Hornik, Maxwell Stinchcombe, and Halbert White. Multilayer feedforward networks are universal approximators. *Neural Networks*, 2(5):359–366, 1989. doi: 10.1016/0893-6080(89)90020-8. URL <https://www.sciencedirect.com/science/article/pii/0893608089900208>. ID: 271125.
- Kurt Hornik, Maxwell Stinchcombe, and Halbert White. Universal approximation of an unknown mapping and its derivatives using multilayer feedforward networks. *Neural Networks*, 3(5):551–560, 1990. doi: 10.1016/0893-6080(90)90005-6.
- Yuchin Juan, Yong Zhuang, Wei-Sheng Chin, and Chih-Jen Lin. Field-aware factorization machines for ctr prediction. In *10th ACM Conference on Recommender Systems*, RecSys ’16, page 43–50, New York, NY, USA, 2016. Association for Computing Machinery. ISBN 9781450340359. doi: 10.1145/2959100.2959134. URL <https://doi.org/10.1145/2959100.2959134>.
- Alex Krizhevsky, Ilya Sutskever, and Geoffrey E. Hinton. Imagenet classification with deep convolutional neural networks. *Communications of the ACM*, 60(6):84–90, 2017.
- Yann LeCun, Léon Bottou, Yoshua Bengio, and Patrick Haffner. Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86(11):2278–2324, 1998.

- Lihong Li, Wei Chu, John Langford, and Robert E. Schapire. A contextual-bandit approach to personalized news article recommendation. In *Proceedings of the 19th International Conference on World Wide Web, WWW '10*, page 661–670, New York, NY, USA, 2010. Association for Computing Machinery. ISBN 9781605587998. doi: 10.1145/1772690.1772758. URL <https://doi.org/10.1145/1772690.1772758>.
- Bin Liu, Ruiming Tang, Yingzhi Chen, Jinkai Yu, Huifeng Guo, and Yuzhou Zhang. Feature generation by convolutional neural network for click-through rate prediction. In *The World Wide Web Conference*, page 1119–1129, 2019.
- Zhongqi Lu and Qiang Yang. Partially observable markov decision process for recommender systems. *CoRR*, abs/1608.07793, 2016. URL <http://arxiv.org/abs/1608.07793>. 1608.07793.
- Tariq Mahmood and Francesco Ricci. Learning and adaptivity in interactive recommender systems. In *Proceedings of the Ninth International Conference on Electronic Commerce, ICEC '07*, page 75–84, New York, NY, USA, 2007. Association for Computing Machinery. ISBN 9781595937001. doi: 10.1145/1282100.1282114. URL <https://doi.org/10.1145/1282100.1282114>.
- Volodymyr Mnih, Koray Kavukcuoglu, David Silver, Andrei A. Rusu, Joel Veness, Marc G. Bellemare, Alex Graves, Martin Riedmiller, Andreas K. Fidjeland, Georg Ostrovski, Stig Petersen, Charles Beattie, Amir Sadik, Ioannis Antonoglou, Helen King, Dharshan Kumaran, Daan Wierstra, Shane Legg, and Demis Hassabis. Human-level control through deep reinforcement learning. *Nature*, 518(7540):529–533, February 26 2015. doi: 10.1038/nature14236. LR: 20220408; JID: 0410462; CIN: Nature. 2015 Feb 26;518(7540):486-7. doi: 10.1038/518486a. PMID: 25719660; 2014/07/10 00:00 [received]; 2015/01/16 00:00 [accepted]; 2015/02/27 06:00 [entrez]; 2015/02/27 06:00 [pubmed]; 2015/04/16 06:00 [medline]; AID: nature14236 [pii]; ppublish.
- Ciara Pike-Burke. Optimism/thompson sampling, 2024.
- Martin L Puterman. *Markov decision processes: discrete stochastic dynamic programming*. John Wiley & Sons, 2014.
- Yanru Qu, Han Chai, Kan Ren, Weinan Zhang, Yong Yu, Ying Wen, and Jun Wang. Product-based neural networks for user response prediction. In *2016 IEEE 16th International Conference on Data Mining (ICDM)*, pages 1149–1154. IEEE, 2016. ISBN 2374-8486. doi: 10.1109/ICDM.2016.0151. ID: 1.
- Steffen Rendle. Factorization machines. In *2010 IEEE International Conference on Data Mining*, pages 995–1000, 2010. ISBN 1550-4786. doi: 10.1109/ICDM.2010.127. ID: 1.
- Matthew Richardson, Ewa Dominowska, and Robert Ragno. Predicting clicks: Estimating the click-through rate for new ads. In *International Conference on World Wide Web, WWW '07*, page 521–530, New York, NY, USA, 2007. Association for Computing Machinery. doi: 10.1145/1242572.1242643. URL <https://doi.org/10.1145/1242572.1242643>.

- Weichen Shen. Deepctr: Easy-to-use, modular and extendible package of deep-learning based ctr models, 2017. URL <https://github.com/shenweichen/deepctr>.
- Song, Shi, Xiao, Duan, Xu, Zhang, and Tang. AutoInt, -11-03 2019.
- Jean-Baptiste Tien, joycenv, and Olivier Chapelle. Display advertising challenge, 2014. URL <https://kaggle.com/competitions/criteo-display-ad-challenge>.
- Steve Wang and Will Cukierski. Click-through rate prediction, 2014. URL <https://kaggle.com/competitions/avazu-ctr-prediction>.
- Xu Wang, Sen Wang, Xingxing Liang, Dawei Zhao, Jincai Huang, Xin Xu, Bin Dai, and Qiguang Miao. Deep reinforcement learning: A survey. *IEEE Transactions on Neural Networks and Learning Systems*, 35(4):5064–5078, 2024. doi: 10.1109/TNNLS.2022.3207346.
- Christopher John Cornish Hellaby Watkins. *Learning from delayed rewards*. PhD thesis, 1989.
- Kevin Webster. Week 2: Multilayer perceptron, 2024.
- Jun Xiao, Hao Ye, Xiangnan He, Hanwang Zhang, Fei Wu, and Tat-Seng Chua. Attentional factorization machines: Learning the weight of feature interactions via attention networks *, 2017. URL <https://arxiv.org/abs/1708.04617>.
- Chunqiu Zeng, Qing Wang, Shekoofeh Mokhtari, and Tao Li. Online context-aware recommendation with time varying multi-armed bandit. In *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, KDD '16, page 2025–2034, New York, NY, USA, 2016. Association for Computing Machinery. ISBN 9781450342322. doi: 10.1145/2939672.2939878. URL <https://doi.org/10.1145/2939672.2939878>.
- Pengtao Zhang and Junlin Zhang. Memonet: Memorizing all cross features' representations efficiently via multi-hash codebook network for ctr prediction, -10-21 2023.
- Weinan Zhang, Tianming Du, and Jun Wang. Deep learning over multi-field categorical data: A case study on user response prediction, 2016. URL <https://arxiv.org/abs/1601.02376>. 1601.02376.
- Weinan Zhang, Jiarui Qin, Wei Guo, Ruiming Tang, and Xiuqiang He. Deep learning for click-through rate estimation, 21 Apr 2021. URL <https://arxiv.org/abs/2104.10584>.
- Guanjie Zheng, Fuzheng Zhang, Zihan Zheng, Yang Xiang, Nicholas Jing Yuan, Xing Xie, and Zhenhui Li. Drn: A deep reinforcement learning framework for news recommendation. In *2018 World Wide Web Conference*, pages 167–176, Lyon, France, 2018. International World Wide Web Conferences Steering Committee. doi: 10.1145/3178876.3185994. URL <https://doi.org/10.1145/3178876.3185994>.