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A Modular Task-oriented Dialogue System Using a Neural Mixture-of-Experts

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ABSTRACT
End-to-end Task-oriented Dialogue Systems (TDSs) have attracted a lot of attention for their superiority (e.g., in terms of global optimization) over pipeline modularized TDSs. Previous studies on end-to-end TDSs use a single-module model to generate responses for complex dialogue contexts. However, no model consistently outperforms the others in all cases.

We propose a neural Modular Task-oriented Dialogue System (MTDS) framework, in which a few expert bots are combined to generate the response for a given dialogue context. MTDS consists of a chair bot and several expert bots. Each expert bot is specialized for a particular situation, e.g., one domain, one type of action of a system, etc. The chair bot coordinates multiple expert bots and adaptively selects an expert bot to generate the appropriate response. We further propose a Token-level Mixture-of-Expert (TokenMoE) model to implement MTDS, where the expert bots predict multiple tokens at each timestamp and the chair bot determines the final generated token by fully taking into consideration the outputs of all expert bots. Both the chair bot and the expert bots are jointly trained in an end-to-end fashion.

To verify the effectiveness of TokenMoE, we carry out extensive experiments on a benchmark dataset. Compared with the baseline using a single-module model, our TokenMoE improves the performance by 8.1% of Inform rate and 0.8% of success rate.

CCS CONCEPTS
• Computing methodologies → Discourse, dialogue and pragmatics; • Information systems → Search interfaces.

KEYWORDS
Task-oriented dialogue systems, Mixture of experts, Neural networks

1 INTRODUCTION
As an important branch of spoken dialogue systems, Task-oriented Dialogue Systems (TDSs) have raised considerable interest due to their broad applicability, e.g., for booking flight tickets or scheduling meetings [30, 33]. Unlike open-ended dialogue systems [23], TDSs aim to assist users to achieve specific goals.

Existing TDS methods can be divided into two broad categories: modularized pipeline TDSs [3, 6, 33] and end-to-end single-module TDSs [12, 28]. The former decomposes the task-oriented dialogue task into modularized pipelines that are addressed by separate models while the latter proposes to use an end-to-end model to solve the task. End-to-end single-module TDSs have many attractive characteristics, e.g., global optimization and easier adaptation to new domains [6]. However, existing studies on end-to-end single-module TDSs mostly generates a response token by token, where each token is drawn from only one distribution over output vocabulary. We think this is unreasonable because the distribution differs a lot among different intents. Actually, more and more empirical studies from different machine learning applications suggest that no model consistently outperforms all others in all cases [9, 19].

Inspired by this intuition, we propose a new Modular Task-oriented Dialogue System (MTDS) framework, as shown in Fig. 1. MTDS consists of a chair bot and several expert bots. Each expert bot is specialized for a particular situation, e.g., one domain, one type of action of a system, etc. The chair bot coordinates multiple expert bots and adaptively selects an expert bot to generate the final response. Compared with existing end-to-end single-module TDSs, the advantages of MTDSs are two-fold. First, the specialization of different expert bots and the use of a dynamic chair bot for combining the outputs breaks the bottleneck of a single model. Second, it is more easily traceable: we can analyze who is to blame when the model makes a mistake. Under this framework, we further propose a neural Mixture-of-Expert (MOE) model, namely Token-level Mixture-of-Expert (TokenMoE), where the expert bots predict

Figure 1: Modular Task-oriented Dialogue System (MTDS) framework.
We propose the MTDS framework, which consists of two types of modules as shown in Figure 1:

- **k** expert bots, each of which is specialized for a particular situation, namely intent (e.g., one domain, one type of action of a system, etc.). Those intents partition dataset \( \mathcal{D} \) into \( k \) pieces \( \mathcal{S} = \{ \mathcal{S}_j \}_{j=1}^k \), where \( \mathcal{S}_j = \{(X^j, Y^j)\} \). Each expert is trained to predict \( p_l(Y^j|X^j) \). We expect the \( l \)-th expert generally performs better than the others on \( \mathcal{S}_j \).
- a chair bot, which learns to coordinate a group of expert bots to make an optimal decision. The chair bot is trained to predict \( p(Y|X) \), where \((X, Y)\) is any sample pair from \( \mathcal{D} \).

2.2 TokenMoE model

In this section, we introduce TokenMoE, a token-level implementation of the MTDS framework. As shown in Figure 2, TokenMoE consists of three types of components, i.e., a shared encoder, \( k \) expert decoders, and a chair decoder.

**Shared context encoder.** The role of shared context encoder is to read the dialogue context sequence and construct their representations at each timestamp. Here we follow Budylinowski et al. [5] and employ a Long Short-Term Memory (LSTM) [14] to map the input sequence \( X \) to hidden vectors \( \{h_1, \ldots, h_m\} \). The hidden vector \( h_i \) at timestep \( i \)-th can be represented as:

\[
    h_i, s_i = \text{LSTM}(\text{emb}(x_i), h_{i-1}, s_{i-1}),
\]

where \( \text{emb}(x_i) \) is the embedding of the token \( x_i \) at \( i \). The initial state of LSTM \( s_0 \) is set to 0.

**Expert decoder.** The \( l \)-th expert outputs the probability \( p_l^j \) over the vocabulary set \( \mathcal{V} \) at \( j \)-th step by:

\[
    p_l^j = \text{softmax}(U^T \omega_l^j + a),
\]

\[
    o_{l,j}, s_{l,j} = \text{LSTM}(y_{l,j-1} \oplus o_{l,j-1}, s_{l,j-1}),
\]

where \( U, a \) are learnable matrices. \( s_{l,j} \) is the state vector which is initialized by the last state of the shared context encoder. \( y_{l,j-1} \) is...
is the generated token at timestamp $j - 1$ by expert $l$. $c_j^k$ is the context vector which is calculated with a concatenation attention mechanism [1, 18] over the hidden representations from shared context encoder.

$$c_j^k = \sum_{i=1}^{m} \alpha_{ji}^k h_i,$$

(3)

$$\alpha_{ji}^k = \frac{\exp(w_{ji}^k)}{\sum_{i=1}^{m} \exp(w_{ji}^k)},$$

$$w_{ji}^k = v^T \tanh(W^h(h_i \oplus s_{j-1}^k) + b),$$

where $\alpha$ is the attention weights; $\oplus$ is the concatenation operation. $W$, $b$, $v$ are learnable parameters, which are not shared by different experts in our experiments.

**Chair decoder.** The chair decoder estimates the final token prediction distribution $p_j$ by combining prediction distribution of all experts (including chair itself) with a proposed token-level Mixture-of-Expert (MOE) scheme. As shown in Fig. 2(b), following the typical neural MOE architecture [22, 24], $p_j$ is computed based on the state $s_j$ and token prediction distribution $p_j^{k+1}$ from all experts (including chair itself) at $j$ as follows.

$$p_j = \sum_{l=1}^{k+1} \beta_j^l \cdot p_j^l,$$

(4)

where $p_j^{k+1}$ is the prediction of the chair, which employs the same architecture of the other experts but is trained on all data. $\beta_j^l$ is the normalized importance scores that can be computed as:

$$\beta_j^l = \frac{\exp(u_j^T u_{c,l})}{\sum_{b=1}^{k} \exp(u_j^T u_{c,b})},$$

(5)

$$u_j = \text{MLP}(h),$$

$$h = s_j^l \oplus p_j^l \oplus \cdots \oplus s_j^k \oplus p_j^k \oplus s_j^{k+1} \oplus p_j^{k+1},$$

where $u_{c,l}$ is an expert-specific, learnable vector that reflects which dimension of the projected hidden representation is highlighted for the expert.

**Loss function.** We devise a global-and-local learning scheme to train TokenMoE. Each expert $l$ is optimized by a localized expert loss defined on $S_l$, which forces each expert to specialize on one of the portions of data $S_l$. We use cross-entropy loss for each expert and the joint loss for all experts are as follows.

$$L_{\text{experts}} = \sum_{l=1}^{k+1} \sum_{(x_j^l, y_j^l) \in S_l} \sum_{j=1}^{n} \mu_j y_j^l \log p_j^l,$$

(6)

where $p_j^l$ is the token prediction by expert $l$ (Eq. 2) computed on the $r$-th data sample; $y_j^l$ is a one-hot vector indicating the ground-truth token at $j$; and $\mu_j$ is the weight of the $k$-th expert.

We also design the global chair loss to differentiate the loss incurred from different experts. The chair can attribute the source of errors to the expert in charge. For each data sample in $D$, we follow the MOE architecture and calculate the combined taken

| Variants | $p_j$ (Eq. 2) | $\mu_k$ (Eq. 6) | $\lambda$ (Eq. 8) |
|----------|---------------|-----------------|-----------------|
| S1       | MOE           | learnable       | learnable       |
| S2       | MOE           | -               | 0.0             |
| S3       | w/o MOE       | $\frac{1}{5}$   | 0.5             |
| S4       | MOE           | $\frac{1}{5}$   | 0.5             |
Table 2: Performance of the single-module baseline (S2SAttnLSTM) and its three variations (V1, V2 and V3) on different domains. Bold highlighted results indicate a statistically significant improvement of a metric over the strongest baseline on the same domain (paired t-test, $p < 0.01$). UNK denotes a unknown domain excluding the domains described in §3.4. Please note that the number of the evaluated dialogue turns varies among different domains.

| Domain  | Inform (%) | Success (%) | BLEU (%) | Score |
|---------|------------|-------------|----------|-------|
|         | Baseline /V1 /V2 /V3 Baseline /V1 /V2 /V3 Baseline /V1 /V2 /V3 # of turns |
| Attraction | 87.20 86.20 91.80 88.70 15.14 14.95 16.08 14.86 99.39 95.45 103.83 101.06 1042 |
| Hotel    | 89.90 93.90 89.90 90.30 87.50 91.70 87.40 89.10 16.60 15.60 15.11 14.13 105.30 108.40 103.76 103.83 1068 |
| Restaurant | 89.20 91.70 86.40 86.10 85.80 87.80 84.00 83.40 17.07 17.70 16.07 17.34 104.57 107.45 101.27 102.09 1024 |
| Taxi     | 100.00 100.00 100.00 100.00 99.90 99.80 99.90 99.80 17.33 19.18 20.13 18.32 117.28 119.08 120.08 118.22 395 |
| Train    | 77.70 77.70 79.00 81.60 75.60 74.80 77.20 79.60 20.35 15.64 22.81 20.62 97.00 91.89 101.42 101.81 1702 |
| Booking  | 100.00 100.00 100.00 100.00 100.00 100.00 100.00 100.00 22.05 21.61 21.96 22.06 122.05 121.61 121.96 122.06 1407 |
| General  | 100.00 100.00 100.00 100.00 100.00 100.00 100.00 100.00 20.21 19.53 20.13 20.80 120.21 119.53 120.13 120.80 2596 |
| UNK      | 100.00 100.00 100.00 100.00 100.00 100.00 100.00 100.00 12.40 11.75 13.12 11.80 112.40 111.75 113.12 111.80 81 |

To answer RQ3, we explore different settings of the learning schemes by considering alternative choices of $p_j$ in Eq. 4, $p_k$ in Eq. 6 and $\lambda$ in Eq. 8. We summarize different variants in Table 1.

In this work, we are focusing on context-to-task [5], so natural language generation (NLG) baselines (e.g., SC-LSTM [27]) will not be taken into consideration.

### 3.3 Implementation details

The vocabulary size is the same as in the original paper that releases the dataset [5], which has 400 tokens. Out-of-vocabulary words are replaced with "$<UNK>\$". We set the word embedding size to 50 and all LSTM hidden state sizes to 150. We use Adam [15] as our optimization algorithm with hyperparameters $\alpha = 0.005$, $\beta_1 = 0.9$, $\beta_2 = 0.999$ and $\epsilon = 10^{-8}$. We also apply gradient clipping [20] with range $[-5, 5]$ during training. We use $l_2$ regularization to alleviate overfitting, the weight of which is set to 0.0001. We set mini-batch size to 64. We use greedy search to generate the response during testing. Extra techniques (e.g., beam search) are not incorporated, because our main concern is the modular model outperforms single-module model instead of the effectiveness of these popular techniques.

### 3.4 Dataset

Our experiments are conducted on the Multi-Domain Wizard-of-Oz (MultiWOZ) [5] dataset. This is the latest large-scale human-to-human TDS dataset with rich semantic labels (e.g., domains and dialogue actions) and benchmark results of response generation. MultiWOZ consists of ~10k natural conversations between a tourist and a clerk. We consider 6 specific action-related domains (i.e., Attraction, Hotel, Restaurant, Taxi, Train, and Booking) and 1 universal domain (i.e., General). 67.37% of dialogues are cross-domain which covers 2–5 domains on average. The average number of turns per dialogue is 13.68 and a turn contains 13.18 tokens on average. To facilitate reproducibility of the results, the dataset is randomly split into 8,438/1,000/1,000 dialogues for training, validation, and testing, respectively.

### 3.5 Evaluation metrics

We use three commonly used evaluation metrics [5]:

- **Inform.** The fraction of responses that provide a correct entity out of all responses.

- **Success.** The fraction of responses that answer all the requested attributes out of all responses.

- **BLEU.** This is a score for comparing a generated response to one or more reference responses.

Following Budzianowski et al. [4], we use $\text{Score} = 0.5^*\text{Inform} + 0.5^*\text{Success} + \text{BLEU}$ as the selection criterion to choose the best model on the validation set and report the performance of the model on the test set. We utilize a paired t-test to show statistical significance ($p < 0.01$) of relative improvements.

### 4 RESULTS

This section describes the results of our experiments and answers research questions proposed in §3.

#### 4.1 Performance of single-module TDSs on different domains (RQ1)

To answer RQ1, we assess the performance of the single-module baseline S2SAttnLSTM and its three variants with settings (V1, V2, and V3) described in §3.2 on different domains. The results are shown in Table 2.

We can see that none of those models can consistently outperform the others on all domains and all metrics. That is to say, a model can achieve its best performance only in some particular situations. To be specific, S2SAttnLSTM achieves its best performance on the Hotel domain in terms of BLEU and Taxi domain in terms of Success. S2SAttnLSTM/V1 outperforms all other models on the Restaurant domain on all metrics and on the Hotel domain (except for BLEU). S2SAttnLSTM/V2 beats the others on the Attraction and Taxi domains in terms of all metrics. S2SAttnLSTM/V3 performs best on the Booking and General domains in terms of BLEU and Score. Overall, S2SAttnLSTM/V1 specializes in, and leads on, the Hotel and Restaurant domains. S2SAttnLSTM/V2 acts as an expert bot specialized for the Attraction, Taxi, UNK domains, and S2SAttnLSTM/V3 serves as an expert bot for the Train, Booking, General domains. Generally, the experimental results verify the assumption and motivation of our MTDS framework.

#### 4.2 Overall performance (RQ2)

To answer our main research question, RQ2, we evaluate the performance of TokenMoE and the baselines (S2SAttnLSTM, TokenMoE...
and their variants with settings V1, V2, V3). The results are shown in Table 3.

Table 3: Comparison between TokenMoE, the benchmark baseline S2SAttnLSTM, and their variant models using setting V1, V2, V3, respectively. Bold results indicate a statistically significant improvement over the strongest baseline (paired t-test, \( p < 0.01 \)).

| Model               | Inform (%) | Success (%) | BLEU (%) | Score  |
|---------------------|------------|-------------|----------|--------|
| S2SAttnLSTM [5]     | 67.20      | 57.20       | 17.83    | 80.03  |
| S2SAttnLSTM/V1      | 63.60      | 52.20       | 18.10    | 76.00  |
| S2SAttnLSTM/V2      | 67.20      | 58.90       | 20.85    | 83.90  |
| S2SAttnLSTM/V3      | 68.60      | 59.30       | 19.41    | 83.36  |
| TokenMoE/V1         | 64.00      | 52.50       | 18.95    | 77.20  |
| TokenMoE/V2         | 62.60      | 54.30       | 18.90    | 77.35  |
| TokenMoE/V3         | 62.90      | 54.00       | 18.34    | 76.79  |
| TokenMoE            | 75.30      | 59.70       | 16.81    | 84.31  |

First, TokenMoE outperforms all baseline models by a large margin in terms of all metrics. Especially, TokenMoE significantly outperforms the benchmark single-module baseline S2SAttnLSTM, by 8.1% of Inform and 2.5% of Success, which maintains the same settings as the original paper [5]. This shows that TokenMoE has an advantage of task completion by providing more appropriate entities and answering the requested attributes as many as possible.

Second, TokenMoE greatly outperforms TokenMoE/V1 by 11.7% on Inform and 7.5% on Success. This is true with S2SAttnLSTM and S2SAttnLSTM/V1 except that the improvements are smaller, i.e., 3.6% on Inform and 5.0% on Success. On the one hand, this means that the attention mechanism is effective. On the other hand, this also shows that the attention mechanisms under our TokenMoE can be more effective and have an even more important role to play. That is to say, the MTDS framework has more potential to improve by separating the modeling of expert and chair bots. TokenMoE/V2 is inferior to S2SAttnLSTM/V2 when changing the LSTM cell as GRU. Similarly, TokenMoE/V3 is less effective than S2SAttnLSTM/V3 when decreasing the number of hidden units. This indicates that TokenMoE is more sensitive to the number of parameters, which shows that it is not effective to learn \( \mu_k \) and \( \lambda \) as learnable parameters while the others regard them as hyperparameters.

Table 4: An example of the generated responses of S2SAttnLSTM and TokenMoE. A user would prefer to get detail information of the train before booking a ticket.

| Model               | Response | Score  |
|---------------------|----------|--------|
| S2SAttnLSTM         | i have [value_count] trains that match your criteria . would you like me to book it for you ? |        |
| TokenMoE            | i have train [train_id] that leaves at [value_time] and arrives at [value_time] . would you like me to book it ? |        |

Table 5: Comparison of TokenMoE with different learning schemes (S1, S2, S3, S4) and the benchmark baseline S2SAttnLSTM. Bold results indicate a statistically significant improvement over the strongest baseline (paired t-test, \( p < 0.01 \)).

| Model               | Inform (%) | Success (%) | BLEU (%) | Score  |
|---------------------|------------|-------------|----------|--------|
| S2SAttnLSTM/V2      | 67.20      | 58.90       | 20.85    | 83.90  |
| TokenMoE/S1         | 66.20      | 54.90       | 19.11    | 79.66  |
| TokenMoE/S2         | 66.50      | 56.90       | 19.48    | 81.18  |
| TokenMoE/S3         | 70.60      | 60.60       | 18.67    | 84.27  |
| TokenMoE/S4         | 75.30      | 59.70       | 16.81    | 84.31  |

First, S1 is worse than the other three variants on all metrics, which shows that it is not effective to learn \( \mu_k \) and \( \lambda \). The reason is that TokenMoE may fall into the optimization trap due to learning \( \mu_k \) and \( \lambda \). That is, TokenMoE learns a very small weight for the local loss of each expert (i.e., \( \mu_k \approx 0 \)) and a large weight for the global loss of the chair bot (i.e., \( \lambda \approx 1 \)). Afterwards, this loss will never decrease any more, so the model learns nothing useful.

Second, S2 is even worse than S2SAttnLSTM/V2 on all metrics which means the performance cannot be improved with the proposed token-level MOE alone. We believe the reason is that token-level MOE makes the model harder to learn, i.e., the model needs to learn not only each prediction distribution by the expert and chair bots but also their combinations. This can be verified by the fact that with token-level MOE and global-and-local learning, S4 further improves Inform by 4.7% compared with S3. Our explanation is that the global-and-local learning makes token-level MOE easier to learn by incorporating supervisions on both the prediction distribution of each expert (local loss in Eq. 6) and their combination (global loss in Eq. 8).

Third, S3 is better than S2SAttnLSTM/V2 in terms of Inform and Success. Also, it achieves the best performance on Success. This shows that TokenMoE with an appropriate scheme is expert in task accomplishment for a TDS, i.e., TokenMoE/S3 is able to generate...
more correct entities and answer more requested attributes. The reason behind this is quite clear: with global-and-local learning, each expert is trained to specialize on a particular domain, which means the chair and the experts are able to extract more manifold candidate tokens, each of them holds a unique preference distribution over the output vocabulary. For example, a Booking expert has a high probability to produce the intent-oriented token “booked” in the response “Your order has been booked”. In contrast, without global-and-local learning, the single model prefers to generate more generic tokens (e.g., “thanks”) that occur most frequently in all domains.

However, it is worth noting that both S2 and S3 are worse than S2SAttnLSTM/V2 on BLEU and S4 is even worse than S2 and S3. This indicates that token-level MOE and global-and-local learning have a negative influence on the response fluency evaluated by BLEU. A possible reason is that various candidate tokens from the chair and experts make the dialogue contexts more complex, which increases the difficulty of generating a fluent response. Another reason is that BLEU is not an ideal metric for dialogue generation task, as we discussed in §4.2.

5 RELATED WORK

There are two dominant frameworks for TDSs: modularized pipeline TDSs and end-to-end single-module TDSs.

5.1 Modularized pipeline TDSs

Modularized pipeline TDSs frameworks consists of a pipeline with several modules. Examples include Natural Language Understanding (NLU) [2, 7], Dialogue State Tracking (DST) [21, 34], Policy Learning (PL), and Natural Language Generation (NLG) [10, 32]. Each module has an explicitly decomposed function for a specialized subtask, which is beneficial to track errors. Young et al. [33] summarize typical pipeline TDSs that are constitutive of distinct modules following a POMDP paradigm. Crook et al. [8] develop a TDS platform that is loosely decomposed into three modules, i.e., input processing of input, dialogue state updates, and policy execution. Yan et al. [31] present a TDS for completing various purchase-related tasks by optimizing individual upstream-dependent modules, i.e., query understanding, state tracking and dialogue management. However, the pipeline setting of these methods will unavoidably incur upstream propagation problem [6], module interdependence problem [6] and joint evaluation problem [33]. Unlike the methods listed above, our MTDS consists of a group of modules including a chair bot and several expert bots. This design addresses the module interdependence problem since each module is independent among the others. Besides, the chair bot alleviates the error propagation problem because it is able to manage the overall errors through an effective learning schemes.

5.2 End-to-end single-module TDSs

End-to-end single-module systems address the TDS task with only one module, which maps a dialogue context to a response directly [29]. There is a growing focus in research on end-to-end approaches for TDSs, which can enjoy global optimization and facilitate easier adaptation to new domains [6]. Sordoni et al. [25] show that using an Recurrent Neural Network (RNN) to generate text conditioned on the dialogue history results in more natural conversations. Later improvements have been made by adding an attention mechanism [17, 26], by modeling the hierarchical structure of dialogues [23], or by jointly learning belief spans [16]. However, existing studies on end-to-end TDSs mostly use a single-module underlying model to generate responses for complex dialogue contexts. This is practically problematic because dialogue contexts are very complicated with multiple sources of information [7]. In addition, previous studies show that it is abnormal to find a single model that achieves the best results on the overall task based on empirical studies from different machine learning applications [9, 19].

Different from the methods listed above, which use a single module to achieve TDSs, our MTDS uses multiple modules (expert and chair bots), which makes good use of the specialization of different experts and the generalization of chair for combining the final outputs. Besides, our MTDS model is able to track who is to blame when the model makes a mistake.

6 CONCLUSION AND FUTURE WORK

This paper we have presented a neural Modular Task-oriented Dialogue System (MTDS) framework composed of a chair bot and several expert bots. We have developed a TokenMoE model under this MTDS framework, where the expert bots make multiple token-level predictions at each timestamp and the chair bot predicts the final generated token by fully considering the whole outputs of all expert bots. Both the chair bot and the expert bots are jointly trained in an end-to-end fashion.

We have conducted extensive experiments on the benchmark dataset MultiWOZ and evaluated the performance in terms of four automatic metrics (i.e., Inform, Success, BLEU, and Score). We find that no general single-module TDS model can constantly outperform the others on all metrics. This empirical observation facilitates the design of a new framework, i.e., MTDS framework. We also verify the effectiveness of TokenMoE model compared with the baseline using a single-module model. Our TokenMoE outperforms the best single-module model (S2SAttnLSTM/V2) by 8.1% of inform rate and 0.8% of success rate. Besides, it significantly beats S2SAttnLSTM, the benchmark single-module baseline, by 3.5% of Inform and 4.2% of Success. In addition, the experimental results show that learning scheme is an important factor of our TokenMoE model.

In the future work, we hope to explore Sentence-level Mixture-of-Expert (SentenceMoE) and combine it with the current TokenMoE to see whether the hybrid model will further improve the performance. Besides, we plan to try more fine-grained expert bots (e.g., according to user intents or system actions) and more datasets to test our new framework and model.

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