Found in Translation: Learning Robust Joint Representations by Cyclic Translations between Modalities

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Abstract
Multimodal sentiment analysis is a core research area that studies speaker sentiment expressed from the language, visual, and acoustic modalities. The central challenge in multimodal learning involves inferring joint representations that can process and relate information from these modalities. However, existing work learns joint representations by requiring all modalities as input and as a result, the learned representations may be sensitive to noisy or missing modalities at test time. With the recent success of sequence to sequence (Seq2Seq) models in machine translation, there is an opportunity to explore new ways of learning joint representations that may not require all input modalities at test time. In this paper, we propose a method to learn robust joint representations by translating between modalities. Our method is based on the key insight that translation from a source to a target modality provides a method of learning joint representations using only the source modality as input. We augment modality translations with a cycle consistency loss to ensure that our joint representations retain maximal information from all modalities. Once our translation model is trained with paired multimodal data, we only need data from the source modality at test time for final sentiment prediction. This ensures that our model remains robust from perturbations or missing information in the other modalities. We train our model with a coupled translation-prediction objective and it achieves new state-of-the-art results on multimodal sentiment analysis datasets: CMU-MOSI, ICT-MIMO, and YouTube. Additional experiments show that our model learns increasingly discriminative joint representations with more input modalities while maintaining robustness to missing or perturbed modalities.

Introduction
Sentiment analysis is an open research problem in machine learning and natural language processing which involves identifying a speaker’s opinion (Pang, Lee, and Vaithyanathan 2002). Previously, text-only sentiment analysis through words, phrases, and their compositionality can be found to be insufficient for inferring sentiment content from spoken opinions (Morency, Mihalcea, and Doshi 2011), especially in the presence of rich nonverbal behaviors which can accompany language (Shaffer 2018). As a result, there has been a recent push towards using machine learning methods to learn joint representations from additional information present in the visual and acoustic modalities. This research field has become known as multimodal sentiment analysis and extends the conventional text-based definition of sentiment analysis to a multimodal environment. For example, (Kaushik, Sangwan, and Hansen 2013) explore the additional acoustic modality while (Wöllmer et al. 2013) use the language, visual, and acoustic modalities present in monologue videos to predict sentiment. This push has been further bolstered by the advent of multimodal social media platforms, such as YouTube, Facebook, and VideoLectures which are used to express personal opinions on a worldwide scale. The abundance of multimodal data has led to the creation of multimodal datasets, such as CMU-MOSI (Zadeh et al. 2016) and ICT-MIMO (Wöllmer et al. 2013), as well as deep multimodal models that are highly effective at learning discriminative joint multimodal representations (Liang, Zadeh, and Morency 2018; Tsai et al. 2018; Chen et al. 2017). Existing prior work learns joint representations using multiple modalities as input (Liang et al. 2018; Morency, Mihalcea, and Doshi 2011; Zadeh et al. 2016). However, these joint representations also

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regain all modalities at test time, making them sensitive to noisy or missing modalities at test time (Tran et al. 2017; Cai et al. 2018).

To address this problem, we draw inspiration from the recent success of Seq2Seq models for unsupervised representation learning (Sutskever, Vinyals, and Le 2014; Tu et al. 2016). We propose the Multimodal Cyclic Translation Network model (MCTN) to learn robust joint multimodal representations by translating between modalities. Figure 1 illustrates these translations between two or three modalities. Our method is based on the key insight that translation from a source modality $S$ to a target modality $T$ results in an intermediate representation that captures joint information between modalities $S$ and $T$. MCTN extends this insight using a cyclic translation loss involving both forward translations from source to target modalities, and backward translations from the predicted target back to the source modality. Together, we call these multimodal cyclic translations to ensure that the learned joint representations capture maximal information from both modalities. We also propose a hierarchical MCTN to learn joint representations between a source modality and multiple target modalities. MCTN is trainable end-to-end with a coupled translation-prediction loss which consists of (1) the cyclic translation loss, and (2) a prediction loss to ensure that the learned joint representations are task-specific (i.e. multimodal sentiment analysis). Another advantage of MCTN is that once trained with multimodal data, we only need data from the source modality at test time to infer the joint representation and label. As a result, MCTN is completely robust to test time perturbations or missing information on other modalities.

Even though translation and generation of videos, audios, and text are difficult (Li et al. 2017b), our experiments show that the learned joint representations can help for discriminative tasks: MCTN achieves new state-of-the-art results on multimodal sentiment analysis using the CMU-MOSI (Zadeh et al. 2016), ICT-MMMO (Wöllmer et al. 2013), and YouTube (Morency, Mihalcea, and Doshi 2011) public datasets. Additional experiments show that MCTN learns increasingly discriminative joint representations with more input modalities during training.

### Related Work

Early work on sentiment analysis focused primarily on written text (Pang, Lee, and Vaithyanathan 2002; Pang and Lee 2008; Socher et al. 2013). Recently, multimodal sentiment analysis has gained more research interest (Baltrusaitis, Ahuja, and Morency 2017). Probably the most challenging task in multimodal sentiment analysis is learning a joint representation of multiple modalities. Earlier work used fusion approaches such as concatenation of input features (Ngiam et al. 2011; Lazaridou, Pham, and Baroni 2015). Several neural network models have also been proposed to learn joint multimodal representations. (Liang et al. 2018) presented a multistage approach to learn hierarchical multimodal representations. The Tensor Fusion Network (Zadeh et al. 2017) and its approximate low-rank model (Liu et al. 2018) presented methods based on Cartesian-products to model unimodal, bimodal and trimodal interactions. The Gated Multimodal Embedding model (Chen et al. 2017) learns an on-off switch to filter noisy or contradictory modalities. Other models have proposed using attention (Cheng et al. 2017) and memory mechanisms (Zadeh et al. 2018) to learn multimodal representations.

### Problem Formulation and Notation

A multimodal dataset consists of $N$ labeled video segments defined as $X = (X^l, X^v, X^a)$ for the language, visual, and acoustic modalities respectively. The dataset is indexed by $N$ such that $X = (X_1, X_2, ..., X_N)$ where $X_i = (X_{i}^l, X_{i}^v, X_{i}^a)$. The corresponding labels for these $N$ segments are denoted as $y = (y_1, y_2, ..., y_N)$, $y_i \in \mathbb{R}$. Following prior work, the multimodal data is synchronized by aligning the input based on the boundaries of each word and zero-padding each example to obtain time-series data of the same length (Liang et al. 2018). The $i$th sample is...
given by $X^S_t = (w^{(1)}, w^{(2)}, ..., w^{(L)})$ where $w^{(t)}$ stands for the $t$th word and $L$ is the length of each example. To accompany the language features, we also have a sequence of visual features $X^V_t = (v^{(1)}, v^{(2)}, ..., v^{(L)})$ and acoustic features $X^A_t = (a^{(1)}, a^{(2)}, ..., a^{(L)})$.

### Learning Joint Representations

Learning a joint representation between two modalities $X^S$ and $X^T$ is defined by a parametrized function $f_\theta$ that returns an embedding $E_{ST} = f_\theta(X^S, X^T)$. From there, another function $g_w$ is learned that predicts the label given this joint representation: $y = g_w(E_{ST})$.

Most work follows this framework during both training and testing (Liang et al. 2018; Liu et al. 2018; Tsai et al. 2018; Zadeh et al. 2018). During training, the parameters $\theta$ and $w$ are learned by empirical risk minimization over paired multimodal data and labels in the training set ($X^S_t, X^T_t, y_{tr}$):

$$E_{ST} = f_\theta(X^S_t, X^T_t), \quad \hat{y}_{tr} = g_w(E_{ST}),$$

$$\theta^*, w^* = \arg \min_{\theta, w} \mathbb{E}[\ell(y_{tr}, \hat{y}_{tr})].$$

for a suitable choice of loss function $\ell_y$ over the labels ($tr$ denotes training set).

During testing, paired multimodal data in the test set ($X^S_{te}, X^T_{te}$) are used to infer the label ($te$ denotes test set):

$$E_{ST} = f_w(X^S_{te}, X^T_{te}), \quad \hat{y}_{te} = g_{w^*}(E_{ST}).$$

### Multimodal Cyclic Translation Network

Multimodal Cyclic Translation Network (MCTN) is a neural model that learns robust joint representations by modality translations. Figure 2 shows a detailed description of MCTN for two modalities. Our method is based on the key insight that translation from a source modality $X^S$ to a target modality $X^T$ results in an intermediate representation that captures joint information between modalities $X^S$ and $X^T$, but using only the source modality $X^S$ as input during test time.

To ensure that our model learns joint representations that retain maximal information from all modalities, we use a cycle consistency loss (Zhu et al. 2017) during modality translation. This method can also be seen as a variant of back-translation which has been recently applied to style transfer (Prabhumoye et al. 2018; Zhu et al. 2017) and unsupervised machine translation (Lample et al. 2018). We use back-translation in a multimodal environment where we encourage our translation model to learn informative joint representations but with only the source modality as input. The cycle consistency loss for modality translation starts by decomposing function $f_\theta$ into two parts: an encoder $f_\theta_e$ and a decoder $f_\theta_d$. The encoder takes in $X^S$ as input and returns a joint embedding $E_{S\rightarrow T}$:

$$E_{S\rightarrow T} = f_{\theta_e}(X^S),$$

which the decoder then transforms into target modality $X^T$:

$$X^T = f_{\theta_d}(E_{S\rightarrow T}),$$

following which the decoded modality $T$ is translated back into modality $S$:

$$E_{T\rightarrow S} = f_{\theta_d}(\hat{X}^T), \quad \hat{X}^S = f_{\theta_e}(E_{T\rightarrow S}).$$

The joint representation is learned by using a Seq2Seq model with attention (Bahdanau, Cho, and Bengio 2014) that translates source modality $X^S$ to a target modality $X^T$. While Seq2Seq models have been predominantly used for machine translation, we extend its usage to the realm of multimodal machine learning.

The hidden state output of each time step is based on the previous hidden state along with the input sequence and is constructed using a recurrent network.

$$h_t = \text{RNN}(h_{t-1}, X^S_t) \quad \forall t \in [1, L].$$

The encoder’s output is the concatenation of all hidden states of the encoding RNN,

$$E_{S\rightarrow T} = [h_1, h_2, ..., h_L],$$

where $L$ is the length of the source modality $X^S$.

The decoder maps the representation $E_{S\rightarrow T}$ into the target modality $X^T$. This is performed by decoding each token $X^T_t$ at a time based on $E_{S\rightarrow T}$ and all previous decoded tokens, which is formulated as

$$p(X^T_t) = \prod_{t=1}^{L} p(X^T_t | E_{S\rightarrow T}, X^T_{1:t-1}).$$

MCTN accepts variable-length inputs of $X^S$ and $X^T$, and is trained to maximize the translational condition probability $p(X^T|X^S)$. The best translation sequence is then given by

$$X^T = \arg \max X^T p(X^T|X^S).$$

We use the traditional beam search approach (Sutskever, Vinyals, and Le 2014) for decoding.

To obtain the joint representation for multimodal prediction, we only use the forward translated representation during inference to remove the dependency on the target modality at
test time. If cyclic translation is used, we denote the translated representation with the symbol $x^t$:

$$E_{S\to T} = E_{S\to T}.$$  \hfill (13)

$E_{S\to T}$ is then used for sentiment prediction:

$$\hat{y} = g_w(E_{S\to T}).$$  \hfill (14)

**Coupled Translation-Prediction Objective**

Training is performed with paired multimodal data and labels in the training set $(X_{tr}^S, X_{tr}^T, y_{tr})$. The first two losses are the forward translation loss $L_t$ defined as

$$L_t = E[\ell_X(T(X^T, X^T))],$$  \hfill (15)

and the cycle consistency loss $L_c$ defined as

$$L_c = E[\ell_X(X^S, X^S)]$$  \hfill (16)

where $\ell_X$ and $\ell_X^S$ represent the respective loss functions. We use the Mean Squared Error (MSE) between the ground-truth and translated modalities. Finally, the prediction loss $L_p$ is defined as

$$L_p = E[\ell_y(\hat{y}, y)]$$  \hfill (17)

with a loss function $\ell_y$ defined over the labels.

Our MCTN model is trained end-to-end with a coupled translation-prediction objective function defined as

$$L = \lambda_t L_t + \lambda_c L_c + L_p,$$  \hfill (18)

where $\lambda_t, \lambda_c$ are weighting hyperparameters. MCTN parameters are learned by minimizing this objective function

$$\theta_{c}^*,\theta_{c}^*,w^* = \arg \min_{\theta_{c},\theta_{c},w} [\lambda_t L_t + \lambda_c L_c + L_p].$$  \hfill (19)

Parallel multimodal data is not required at test time. Inference is performed using only the source modality $X^S$:

$$E_{S\to T} = f_{I_{S}}(X^S),$$  \hfill (20)

$$\hat{y} = g_w(E_{S\to T}).$$  \hfill (21)

This is possible because the encoder $f_{I_{S}}$ has been trained to translate the source modality $X^S$ into a joint representation $E_{S\to T}$ that captures information from both source and target modalities.

**Hierarchical MCTN for Three Modalities**

We extend the MCTN in a hierarchical manner to learn joint representations from more than two modalities. Figure 3 shows the case for three modalities. The hierarchical MCTN starts with a source modality $X^S$ and two target modalities $X^T_1$ and $X^T_2$. To learn joint representations, two levels of modality translations are performed. The first level learns a joint representation from $X^S$ and $X^T_1$ using multimodal cyclic translations as defined previously. At the second level, a joint representation is learned hierarchically by translating the first representation $E_{S\to T_1}$ into $X^T_2$. For more than three modalities, the modality translation process can be repeated hierarchically.

Two Seq2Seq models are used in the hierarchical MCTN for three modalities, denoted as encoder-decoder pairs $\{f_{I_{S}}, f_{D_{1}}\}$ and $\{f_{D_{2}}, f_{D_{3}}\}$. A multimodal cyclic translation is first performed between source modality $X^S$ and the first target modality $X^{T_1}$. The forward translation is defined as

$$E_{S\to T_1} = f_{I_{S}}(X^S), \quad X^T_{1_{tr}} = f_{D_{1}}(E_{S\to T_1}),$$  \hfill (22)

and followed by the decoded modality $X^{T_1}$ being translated back into modality $X^S$:

$$E_{T_1\to S} = f_{I_{T_1}}(X_{T_1}^T), \quad \hat{X}^S_{T_1} = f_{D_{S}}(E_{T_1\to S}).$$  \hfill (23)

A second hierarchical Seq2Seq model is applied on the outputs of the first encoder $f_{I_{S}}$:

$$E_{S\to T_1} = E_{S\to T_1},$$  \hfill (24)

$$E_{S\to T_2} = f_{I_{S}}(E_{S\to T_2}), \quad X^T_{2_{tr}} = f_{D_{2}}(E_{S\to T_2}).$$  \hfill (25)

The joint representation between modalities $X^S$, $X^{T_1}$, and $X^{T_2}$ is now $E_{S\to T_2}$. It is used for sentiment prediction via a recurrent neural network via regression method.

Training the hierarchical MCTN involves computing a cyclic consistent loss for modality $T_1$, given by the respective forward translation loss $L_{t_1}$ and the cycle consistency loss $L_{c_1}$. We do not use a cyclic translation loss when translating from $E_{S\to T_1}$ to $X^{T_2}$ since the ground truth $E_{S\to T_1}$ is unknown, and so only the translation loss $L_{t_2}$ is computed. The final objective for hierarchical MCTN is given by

$$L = \lambda_t L_{t_1} + \lambda_c L_{c_1} + \lambda_t L_{t_2} + L_p.$$  \hfill (26)

We emphasize that for MCTN with three modalities, only a single source modality $X^S$ is required at test time. Therefore, MCTN has a significant advantage over existing models since it is robust to noisy or missing target modalities.
We use the CMU Multimodal Opinion-level Sentiment Inten-
sity dataset (CMU-MOSI) which contains 2199 video se-
gments each with a sentiment label in the range $[-3, +3]$. To
be consistent with prior work, we use 52 segments for train-
ing, 10 for validation and 31 for testing. The same speaker
does not appear in both training and testing sets to ensure that
our model learns speaker-independent representations. We
also run experiments on ICT-MMMO (Wöllmer et al. 2013)
and YouTube (Morency, Mihalcea, and Doshi 2011) which
consist of online review videos annotated for sentiment.

### Dataset and Input Modalities

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also run experiments on ICT-MMMO (Wöllmer et al. 2013)
and YouTube (Morency, Mihalcea, and Doshi 2011) which
consist of online review videos annotated for sentiment.

### Multimodal Features and Alignment

Following previous work (Liang et al. 2018), GloVe word
embeddings (Pennington, Socher, and Manning 2014), Facet
traits (iMotions 2017), and COVAREP (Degottex et al. 2014)
features are extracted for the language, visual and acoustic
modalities respectively. Forced alignment is performed using
P2FA (Yuan and Liberman 2008) to obtain spoken word
utterance times. The visual and acoustic features are aligned by
computing their average over the utterance interval of each
word.

### Evaluation Metrics

For parameter optimization on CMU-MOSI, the prediction
loss function is set as the Mean Absolute Error (MAE):
$$ f_p(y_{\text{train}}, y_{\text{train}}) = |y_{\text{train}} - y_{\text{train}}|. $$
We report MAE and

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Test Inputs</th>
<th>CMU-MOSI</th>
<th>ICT-MMMO</th>
<th>YouTube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td></td>
<td>Acc(↑)</td>
<td>F1(↑)</td>
<td>MAE(↓)</td>
</tr>
<tr>
<td>Model</td>
<td></td>
<td>Acc(↑)</td>
<td>F1(↑)</td>
<td>Acc(↑)</td>
</tr>
<tr>
<td>RF</td>
<td>${\ell, v, a}$</td>
<td>56.4</td>
<td>56.3</td>
<td>-</td>
</tr>
<tr>
<td>SVM</td>
<td>${\ell, v, a}$</td>
<td>71.6</td>
<td>72.3</td>
<td>1.100</td>
</tr>
<tr>
<td>THMM</td>
<td>${\ell, v, a}$</td>
<td>50.7</td>
<td>45.4</td>
<td>-</td>
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<tr>
<td>EF-HCRF</td>
<td>${\ell, v, a}$</td>
<td>65.3</td>
<td>65.4</td>
<td>-</td>
</tr>
<tr>
<td>MV-HCRF</td>
<td>${\ell, v, a}$</td>
<td>65.6</td>
<td>65.7</td>
<td>-</td>
</tr>
<tr>
<td>DF</td>
<td>${\ell, v, a}$</td>
<td>74.2</td>
<td>74.2</td>
<td>1.143</td>
</tr>
<tr>
<td>DF-LSTM</td>
<td>${\ell, v, a}$</td>
<td>74.3</td>
<td>74.3</td>
<td>1.023</td>
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<tr>
<td>MV-LSTM</td>
<td>${\ell, v, a}$</td>
<td>73.9</td>
<td>74.0</td>
<td>1.019</td>
</tr>
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<td>BC-LSTM</td>
<td>${\ell, v, a}$</td>
<td>75.2</td>
<td>75.3</td>
<td>1.079</td>
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<td>${\ell, v, a}$</td>
<td>74.6</td>
<td>75.4</td>
<td>1.040</td>
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<td>${\ell, v, a}$</td>
<td>76.5</td>
<td>73.4</td>
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<td>${\ell, v, a}$</td>
<td>77.1</td>
<td>77.0</td>
<td>0.968</td>
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<tr>
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<td>${\ell, v, a}$</td>
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<td>77.3</td>
<td>0.965</td>
</tr>
<tr>
<td>LMF</td>
<td>${\ell, v, a}$</td>
<td>76.4</td>
<td>75.7</td>
<td>0.912</td>
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<tr>
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<td>${\ell, v, a}$</td>
<td>78.4</td>
<td>78.0</td>
<td>0.922</td>
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<tr>
<td>MCTN</td>
<td>${\ell}$</td>
<td>79.3</td>
<td>79.1</td>
<td>0.909</td>
</tr>
</tbody>
</table>

Table 1: Sentiment prediction results on CMU-MOSI. Best
results are highlighted in bold. MCTN outperforms the cur-
rent state-of-the-art across most evaluation metrics and uses
only the language modality during testing.

### Experimental Setup

In this section, we describe our experimental methodology to
evaluate the joint representations learned by MCTN.1

#### Base Models

We compare MCTN with previous models
- **RMFN** (Liang et al. 2018) uses a multistage approach to
  learn hierarchical representations (current state-of-the-art on
  CMU-MOSI).
- **LMF** (Liu et al. 2018) approximates the expen-
sive tensor products in **TFN** (Zadeh et al. 2017) with efficient
  low-rank factors.
- **MFN** (Zadeh et al. 2018) synchronizes sequences using a multimodal gated memory. **EF-LSTM** concate-
nates multimodal inputs and uses a single LSTM (Hochre-
ter and Schmidhuber 1997). For a description of other baselines,
please refer to the supplementary material.

### Results and Discussion

This section presents and discusses our experimental results.

#### Comparison with Existing Work

**Q1:** How does MCTN compare with existing state-of-the-art
approaching for multimodal sentiment analysis?

We compare MCTN with previous models3. From Table 1,
MCTN using language as the source modality achieves new
state-of-the-art results on CMU-MOSI for multimodal senti-
ment analysis. State-of-the-art results are also achieved on
ICT-MMMO and YouTube (Table 2). It is important to note
that MCTN only uses language during testing, while other
baselines use all three modalities.

#### Adding More Modalities

**Q2:** What is the impact of increasing the number of modalities
during training for MCTN with cyclic translations?

Pearson’s correlation $r$. We also perform sentiment classi-
fication on CMU-MOSI and report binary accuracy (Acc)
and F1 score (F1). On ICT-MMMO and YouTube, we set
the prediction loss function as categorical cross-entropy and
report sentiment classification and F1 score. For all metrics,
higher values indicate stronger performance, except MAE
where lower values indicate stronger performance.

### Baseline Models

We compare to the following multimodal models:
- **RMFN** (Liang et al. 2018) uses a multistage approach to
  learn hierarchical representations (current state-of-the-art on
  CMU-MOSI).
- **LMF** (Liu et al. 2018) approximates the expen-
sive tensor products in **TFN** (Zadeh et al. 2017) with efficient
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- **MFN** (Zadeh et al. 2018) synchronizes sequences using a multimodal gated memory. **EF-LSTM** concate-
nates multimodal inputs and uses a single LSTM (Hochre-
ter and Schmidhuber 1997). For a description of other baselines,
please refer to the supplementary material.

1Our source code is released at https://github.com/hainow/
MCTN.
2Details on feature extraction are in supplementary material.
3For full results please refer to the supplementary material.
This also implies that cyclic translations are a viable method and using cyclic translations improve discriminative information for sentiment (Zadeh et al. 2017).

In addition, we visually inspect the joint representations learned from MCTN as we add more modalities during training (see Table 5). The joint representations for each segment in CMU-MOSI are extracted from the best performing model for each number of modalities and then projected into two dimensions via the t-SNE algorithm (van der Maaten and Hinton 2008). Each point is colored red or blue depending on whether the video segment is annotated for positive or negative sentiment. From Figure 5, we observe that the joint representations become increasingly separable as the more modalities are added when the MCTN is trained. This is consistent with increasing discriminative performance with more modalities (as seen in Table 3).

### Ablation Studies

We use several models to test our design decisions. Specifically, we evaluate the impact of cyclic translations, modality ordering, and hierarchical structure.
Table 5: Trimodal variations results on CMU-MOSI dataset.

<table>
<thead>
<tr>
<th>Model</th>
<th>CMU-MOSI</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Translation</td>
<td>F1(↑)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acc(t)</td>
</tr>
<tr>
<td>MCTN Trimodal (4e)</td>
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<tr>
<td>(V ⊢ T) → A</td>
<td>56.4</td>
<td>56.3</td>
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<tr>
<td>(T ⊢ V) → T</td>
<td>78.7</td>
<td>78.8</td>
</tr>
<tr>
<td>(A ⊢ T) → T</td>
<td>79.3</td>
<td>79.1</td>
</tr>
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<td></td>
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<tr>
<td>Simple Trimodal (4g)</td>
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<td>(A → V) → T</td>
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<td>(V → T) → A</td>
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<td>(A → T) → V</td>
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<tr>
<td>(T → V) → A</td>
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<td>74.4</td>
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<tr>
<td>[A, T] → V</td>
<td>73.3</td>
<td>73.4</td>
</tr>
<tr>
<td>[T, V] → A</td>
<td>72.3</td>
<td>72.3</td>
</tr>
<tr>
<td>Concat Trimodal (4h)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A → [T, V]</td>
<td>55.5</td>
<td>55.6</td>
</tr>
<tr>
<td>T → [A, V]</td>
<td>75.7</td>
<td>75.7</td>
</tr>
<tr>
<td>[T, A] → [T, V]</td>
<td>73.2</td>
<td>73.2</td>
</tr>
<tr>
<td>[T, V] → [T, A]</td>
<td>74.1</td>
<td>74.1</td>
</tr>
<tr>
<td>Paired Trimodal (4i)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[T → A, T → V]</td>
<td>73.8</td>
<td>73.8</td>
</tr>
</tbody>
</table>

Q5: What is the impact of using two Seq2Seq models instead of one shared Seq2Seq model for cyclic translations?

We compare Figure 4(c), which uses one Seq2Seq model for cyclic translations with Figure 4(d), which uses two separate Seq2Seq models: one for forward translation and one for backward translation. We observe from Table 4 that (c) > (d), so using one model with shared parameters is better. This is also true for hierarchical MCTN: (f) > (g) in Table 5. We hypothesize that this is because training two deep Seq2Seq models requires more data and is prone to overfitting. Also, it does not learn only a single joint representation but instead two separate representations.

Q6: What is the impact of using two levels of translations instead of one level when learning from three modalities?

Our hierarchical MCTN is shown in Figure 4(e). In Figure 4(h), we concatenate two modalities as input and use only one phase of translation. From Table 5, we observe that (e) > (h): both levels of modality translations are important in the hierarchical MCTN. We believe that representation learning is easier when the task is broken down recursively: using two translations each between a single pair of modalities, rather than a single translation between all modalities.

Conclusion

This paper investigated learning joint representations via cyclic translations from source to target modalities. During testing, we only need the source modality for prediction which ensures robustness to noisy or missing target modalities. We demonstrate that cyclic translations and seq2seq models are useful for learning joint representations in multimodal environments. In addition to achieving new state-of-the-art results on three datasets, our model learns increasingly discriminative joint representations with more input modalities while maintaining robustness to all target modalities.

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