OBJECT DYNAMICS DISTILLATION FOR SCENE DECOMPOSITION AND REPRESENTATION

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ABSTRACT

The ability to perceive scenes in terms of abstract entities is crucial for us to achieve higher-level intelligence. Recently, several methods have been proposed to learn object-centric representations of scenes with multiple objects, but most of them focus on static images. In this paper, we work on object dynamics and propose Object Dynamics Distillation Network (ODDN) which distills explicit object dynamic representations (e.g., velocity) from raw video input. Furthermore build a relation module that calculates object-pair interactions and applies it to the corresponding dynamic representations of objects. We verify our approach on tasks of video events reasoning and video prediction, which are two important evaluations for video understanding. The results show that visual representations of ODDN perform better in answering reasoning questions around physical events in a video compared to representaions of the previous scene representation methods. And, ODDN could generate reasonable future frames given two input frames, considering occlusion and objects collision. In addition, using the object dynamic clues allows the model to obtain better scene decomposition quality in segmentation and reconstruction.

1 INTRODUCTION

Humans learn to decompose the scene into independent objects to understand the environment at a very early age. This cognitive pattern promotes the generation of common sense of physics, for example, the speed of the object will change after a collision. However, the neural networks seem to lack the ability to acquire a compositional understanding of the world in terms of structured objects, which is crucial for generalizing and higher-level tasks such as planning and reasoning(Greff et al., 2020). To tackle this problem, many scene decomposition approaches have been proposed to segment an image with ground-truth segmentation labels as supervision(Ronneberger et al., 2015; Long et al., 2015; Badrinarayanan et al., 2017; Chen et al., 2017). However, the acquisition of semantic segmentation labels is costly. Besides, these methods do not provide structured representations of segmented areas. Recently, several unsupervised methods have become popular in learning decomposition and object-centric representations of scenes with multiple objects(Hsieh et al., 2018; Van Steenkiste et al., 2018; Burgess et al., 2019; Locatello et al., 2020; Greff et al., 2017; Eslami et al., 2016; Kosiorek et al., 2018), and some of those methods learn disentangled features which represent crucial properties (e.g., 'color', 'size') of object in the same format. The work of (van Steenkiste et al., 2019) has proved that disentangled representations do in fact lead to better downstream task performance.

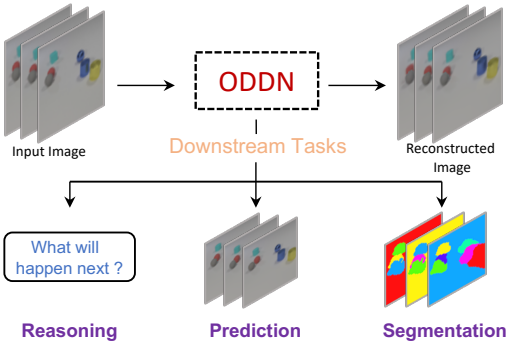

Figure 1: ODDN could be used to handle multiple downstream tasks.

Beyond static scenes (images), people understand dynamic physical events and predict how the future might unfold(Battaglia et al., 2013). Even infants have the intuition that temporarily occluded objects remain coherent wholes and follow spatially contiguous paths(Baillargeon, 1987). This com-

mon sense of physics is inseparable from the understanding of object dynamics. However, existing scene decomposition and representation works focus on images, which means that when interpreting videos, those approaches process one frame at a time, and do not encode objects' dynamic properties. We argue that representing object dynamics is significant for tasks as video reasoning or predicting the future.

In this work, we aim to distill and disentangle object dynamics in an unsupervised manner and present ODDN (Object Dynamics Distillation Network). ODDN is built on a spatial mixtures framework(Greff et al., 2019), a prime example of VAE(Kingma & Welling, 2013) based architecture of decomposing scenes into object-centric latent representations. Formally, the model clusters and decodes pixels into latent representations through an iterative amortized variational inference procedure then reconstructs the latent vectors into input images. In this way, scenes are segmented and represented as object-centric disentangled features. Based ob this, our key insight is that the object dynamics hide in variations between objects' static latent representations of different frames, thus, we design our model to distill object dynamics from their representations of the current and previous frames. With the distilled object dynamics as part of the representation, we further build a relation module to model object interactions.

We evaluate ODDN on different downstream tasks as shown in Figure 1. Results show that representations with object dynamics perform better in reasoning task than representations with static properties only, and the relation module endows ODDN with the capability of predicting the future. In addition, we notice that incorporating object dynamics and relations into the basic scene decomposition framework benefits the segmentation and reconstruction quality.

We highlight contributions of our approach:

- Distillation of disentangled object dynamics from raw video input in an unsupervised manner.
- State-of-the-art performance on CLEVRER(Yi et al., 2019) which focus on video understanding and causal reasoning.
- Capability of future frames prediction in 3D scenes including physical events (occlusion, collision).
- Better scene decomposition quality for spatial mixture architecture in terms of segmentation and reconstruction.

2 RELATED WORK

Object representation of static scenes. Representation learning is an important topic in deep learning. Several recent lines of work making breakthroughs in this area learns representations without explicit supervision. NEM(Greff et al., 2017) builds a spatial mixture model based on EM algorithm to discover a compositional object representation but fails to cope with colored or 3D data. AIR(Eslami et al., 2016) achieves scene interpretation by using a recurrent neural network that attends to one element at a time and disentangles positions and appearances explicitly in latent variables. AIR can decompose 3D scenes, however, it generates partial images separately and adds them together to form the final image, which leads to its restriction: they can't be applied to scenes with occluded objects. MoNet(Burgess et al., 2019) uses multiple attention steps to tackle complex 3D scene, which is the first being capable of discovering object masks and completing partially occluded objects. IODINE(Greff et al., 2019) does the same thing as MoNet by using iterative variational inference to refine the inferred latent representation in each encoding step.

Object representation of dynamic scenes. Methods mentioned above are designed to decompose static scenes, hence they do not encode object dynamics in the latent space. R-NEM(Van Steenkiste et al., 2018) applies RNN to NEM to encode object dynamics implicitly, and models relations between objects to learn physical interaction which enables the model to predict future frames for video input. Similarly, SQAIR(Kosiorek et al., 2018) extends AIR to image sequence to discover and track objects throughout the video frames. Both R-NEM and SQAIR bear the drawbacks of their predecessors. ViMON(Weis et al., 2020) is a video-extension of MoNet by building temporal connections between latent representations with GRU(Cho et al., 2014). ViMON learns a linear transformation to predict next time-step image, encouraging dynamics encoded. PROVIDE(Zablotskaia et al., 2020)

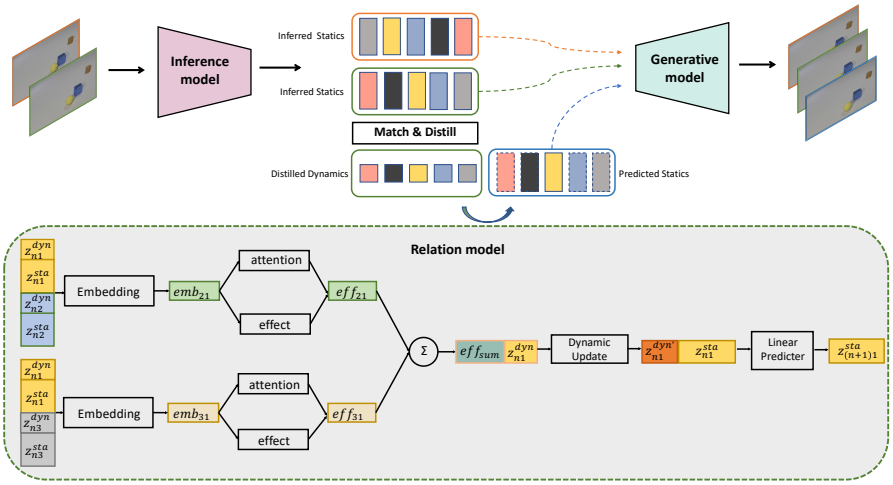

Figure 2: Overview of ODDN. The inference model assigns inputs into K slots per image, each slot encodes object or background into latent space, shown in different colors. We take use of the attention mechanism of transformer to align objects' latents of two input images and encode the aggregated representation into a low-dimensional vector to obtain disentangled object dynamics. Object latents (sta) and dynamics (dyn) are used to model interactions between object-pairs, we show the relation module with three slots as an example, which compute the effects z_2 and z_3 have on z_1. We concat the updated object dynamics and object latents to predict the next frame object latents. The Generative model outputs both reconstructions of input images and prediction of future frame images.

applies 2D-LSTM(Graves et al., 2007) to IODINE and is capable of simulating future video frames. Although ViMON and PROVIDE encode object dynamics, they do not model interactions between objects, thus, they can't handle datasets with object collisions. Besides, object dynamics of both methods are spread in latent space implicitly, which lacks interpretability. It has been proved that disentangled representations allow one to learn models with better performance and fewer samples for downstream reasoning tasks. Therefore, in this work, we aim to represent object dynamics explicitly. Instead of using RNNs, we match objects' latent representations between the current and previous frames and distillate their dynamics by applying a single-layer transformer encoder.

3 METHOD

Our goal is to decompose dynamic scenes into object-centric representations purely based on visual observations. And the representation contains interpretable object dynamics. Recent works decompose static scenes by randomly assigning objects to a fixed number of slots, which share weights to obtain latent vectors with a common format. However, these works do not encode object dynamics for objects of sequential input. Our key idea is that building upon these successful multi-object scenes decomposing and representation approaches, object dynamics could be distilled from the corresponding latent representations of two consecutive frames.

3.1 OBJECT DYNAMICS DISTILLATION NETWORK

We illustrate the framework of ODDN in Figure 2. Formally, ODDN takes as input a video, then the inference model processes all frames $x_{1:N}$ independently to obtain K object latent vectors which encode object static properties. For frames $x_{2:N}$, we distill objects' dynamics from their latent vectors of the current and the previous frames. The relation module takes the object latent vectors and the object dynamics of frames $x_{2:N-1}$ as input, calculates the interaction between objects and predicts object latent representations of frames $x_{3:N}$.

The input image $x \in \mathbb{R}^D$ could be reconstructed by K latent vectors $z_k \in \mathbb{R}^M$, each of which corresponds to one object or background area after training, and each latent vector is also called a

slot. Firstly, latent z_k is decoded into pixel-wise mean μ_{ik} and pixel-wise mask logit $\hat{m}_{ik}$. Then, the K mask logits are normalized with a softmax function to ensure that the sum of K mask logits for each pixel is 1. At last, μ and m parameterize the final spatial Gaussian mixture distribution:

$$p(x|z) = \prod_{i=1}^{D} \sum_{k=1}^{K} m_{ik} \mathcal{N}(x_i; \mu_{ik}, \sigma^2), \tag{1}$$

where σ is the same and fixed for all i and k. The input image can be reconstructed as $\hat{x} = \sum_{k=1}^{K} m_k \mu_k$.

The inference model of ODDN follows previous work (Greff et al., 2019) by using amortized variational inference to infer and refine posterior $q_\lambda(z|x)$ iteratively where $\lambda = \{\mu_z, \sigma_z\}$. The main reason to use such an iterative process is that the standard variational inference framework leads to the multimodal problem, which means that any pixel could be capdtured by any slot. IODINE updates posterior λ as follows:

$$z^t \sim q_\lambda(z^t|x), \tag{2}$$

$$\lambda^{t+1} \leftarrow \lambda^t + f_\phi(z^t, x, a), \tag{3}$$

where the posterior parameters λ start with an arbitrary guess, and the first latent representations z^1 are sampled from q_λ. In each refinement step, input x together with a set of variables a, which are computed from z^t (means μ, masks m, mean gradient $\nabla_\mu \mathcal{L}$, mask gradient $\nabla_m \mathcal{L}$) are fed into a refinement network $f\phi$ to obtain the additive updates for the posterior.

ODDN predicts future objects state in latent space given first two frames:

$$\hat{z}_{nk} = W_{pred}([z^{dyn}_{(n-1)k}; z^{sta}_{(n-1)k}]); \quad n > 2, \tag{4}$$

where z^{dyn} is the distilled object dynamic representation and z^{sta} refers to the object latent representation output by the inference model. The next-frame latent vectors are predicted with a learnable transformation W_{pred}, details will be introduced in section 3.2 and section 3.3.

The whole network is trained end-to-end and the final loss consists of prediction loss $\mathcal{L}_p$ and reconstruction loss $\mathcal{L}_r$, in detail:

$$\mathcal{L}_r(x) = \sum_{n=1}^{N} \sum_{t=1}^{T} \left[-log(p(x_n|z^t_{n\cdot})) + \beta KL(q_\lambda(z^t_{n\cdot}|x_n, z^{<t}_{n\cdot})||p(z) \right], \tag{5}$$

$$\mathcal{L}_p(x) = \sum_{n=3}^{N} \left[-log(p(x_n|\hat{z}_n)) \right], \tag{6}$$

where T is the maximum refinement step number during the inference stage. We measure and optimize the KL divergence between the variational posterior and the prior in $\mathcal{L}_r$.

3.2 DYNAMIC DISTILLATION

In this section, we describe how ODDN derive object dynamics from sequential object latent representations. For existing scene decomposition and representation approaches, object-to-slot assignments usually switch unpredictably in a video. Thus, we draw support from the Transformer to match object latent representations in different frames correctly and further distill object dynamics.

Revisit attention mechanism of Transformer. The key component of the Transformer is the attention module which could be mathematically described as:

$$Attention(q, K, V) = \sum_{i=1}^{|V|} \alpha_i W_v v_i; \alpha_i \propto exp[(W_q q)^T (W_k k_i)], \tag{7}$$

where $q \in \mathbb{R}_d$; K consists of $|K|$ elements $(k_1, k_2, \cdots, k_{|K|})$ with $k_i \in \mathbb{R}_d$; V consists of $|V|$ elements $(v_1, v_2, \cdots, v_{|V|})$ with $v_i \in \mathbb{R}_d$.

This attention function maps the input query q and a set of key(k)-value(v) pairs to an updated representation, W_q, W_k, W_v are learnable parameters. Besides, $\alpha_i \geq 0, \sum_{i=1}^{|v|} \alpha_i = 1$, and usually $|K| = |V|$.

Model architecture. The inference model decomposes the input video into $N * K$ latent vectors, where K is the slot number for each frame and N is the number of frames of the video. We put these sequence consisting latent vectors $\{z_{11}, \cdots, z_{1K}, \cdots, z_{N1}, \cdots, z_{NK}\}$ into one single Transformer encoder layer to match the corresponding slots which usually switch their assignments with objects several times in a video. After finding object correspondence in different frames, the Transformer aggregates latent information and distills object dynamics which are encoded into a low-dimensional representation space. Mathematically, the dynamic distillation process for the k-th slot in the n-th frame could be described as:

$$z'_{nk} = Attention(z_{nk}, \{z_{n-1}, z_n\}, \{z_{n-1}, z_n\}); \quad n > 1, \tag{8}$$

$$z^{dyn}_{nk} = FFN(Norm(z'_{nk} + z_{nk})), \tag{9}$$

where z^{dyn} is a low-dimensional vector transformed by the fully connected feed-forward network (FFN). This learning process is performed in parallel by pre-defining an attention mask to ensure that latent representations of the current frame only attend to ones one frame before.

3.3 RELATION MODULE.

ODDN models interactions between object pairs by computing all object-pair effects and leting them act on and update object dynamics. ODDN learns a soft attention coefficient for each effect. The object dynamics are updated as:

$$emb_{k_i,k_j} = W_{emb}([z^{dyn}_{k_i}; z^{sta}_{k_i}; z^{dyn}_{k_j}; z^{sta}_{k_j}]), \tag{10}$$

$$att_{k_i,k_j} = Sigmoid(W_{att}(emb_{k_i,k_j})), \tag{11}$$

$$eff_{k_i,k_j} = W_{eff}(emb_{k_i,k_j}), E_{k_i} = \sum_{i \neq j} att_{k_i,k_j} * eff_{k_i,k_j}, \tag{12}$$

$$z^{dyn'}_{nk_i} = z^{dyn}_{nk_i} + W_{dyn}(E_{k_i}), \tag{13}$$

where W_{emb} first embeds representations of object-pair, then W_{att} learns the attention coefficient based on the object-pair embedding, and W_{eff} learns the effect z_{k_j} has on z_{k_i}. At last, the summed effects output an update value with W_{dyn}.

We draw inspiration from NPE(Chang et al., 2016) and R-NEM(Van Steenkiste et al., 2018), both architectures model object relations. NPE has access to ground truth representations of scenes and computes effect for each neighborhood object-pair with a neighborhood mask based on ground-truth object position, and finally, the summed effects act on object velocity. R-NEM represents objects in an unsupervised fashion and implicitly encodes sequential information with an RNN(Hochreiter & Schmidhuber, 1997). Instead of using a neighborhood mask, R-NEM learns soft attention for all object-pairs. Our approach learns to represent object dynamics explicitly. Thus, we compute all object-pair effects and let it act on object dynamics as NPE, and learn an attention coefficient for each effect as R-NEM.

After distilling and updating object dynamics, we predict next-frame object latents by simply learning a transformation W_{pred}, and $W_{pred} \in \mathbb{R}^{(L+l)\times L}$, $\hat{z}^{sta}_{(n+1)\cdot} = W_{pred}([z^{dyn'}_{n\cdot}; z^{sta}_{n\cdot}])$, where l indicates the dynamics dimension ($l = 4$ in our experiments).

To alleviate error accumulating when implementing multi-step predicting in the inference stage, we use student forcing strategy during training: instead of only using z_n to predict $\hat{z}_{n+1}$, $\hat{z}_n$ is also used to iteratively roll out a predicted image sequence.

4 EXPERIMENTS

In this section, we design experiments in the perspective of representation, prediction, and scene decomposition. In particular, we study how ODDN performs on tasks of video understanding and reasoning, video prediction, reconstruction, and segmentation. To quantify segmentation quality, we measure the similarity between ground-truth (instance) segmentations and our predicted object masks using the Adjusted Rand Index(Rand, 1971) (ARI) and The Foreground Adjusted Rand Index (F-ARI) which is a modification of the ARI score ignoring background pixels.

Model	Descriptive	Explanatory		Predictive		Counterfactual	
		per opt.	per ques.	per opt.	per ques.	per opt.	per ques.
MAC (V+)(Yi et al., 2019)	86.4	70.5	22.3	59.7	42.9	63.5	25.1
NS-DR(Yi et al., 2019)	88.1	87.6	79.6	82.9	68.7	74.1	42.2
DCL(Chen et al., 2021)	90.7	89.6	82.8	90.5	82.0	80.4	46.5
ALOE(Ding et al., 2021)	94.0	98.5	96.0	93.5	87.5	91.4	75.6
ODDN-ALOE	**95.8**	**98.9**	**97.0**	**95.7**	**91.8**	**93.0**	**80.1**

Table 1: Performance (per question/option accuracy) comparison with the state-of-the-art methods MAC (V+), NS-DR, DCL, and ALOE on CLEVRER, ALOE takes static scene representaions from Monet as visual input while ODDN-ALOE use representations of ODDN.

Feature	Dimension	Dynamic	Descriptive	Explanatory		Predictive		Counterfactual	
				per opt.	per ques.	per opt.	per ques.	per opt.	per ques.
PROVIDE	16	✓	75.2	91.6	77.4	80.5	65.4	76.4	39.4
MoNet w/o ss	16		91.0	-	92.8	-	82.8	-	68.7
IODINE	20		92.8	98.3	95.6	89.1	80.2	89.7	71.3
IODINE	16		93.5	98.1	95.0	91.6	84.5	90.6	73.4
ODDN w/o relation^{-dyn}	16		92.8	97.6	93.6	90.6	82.8	89.2	70.1
ODDN w/o relation	20	✓	93.9	98.2	95.1	93.6	88.0	90.7	73.6
ODDN^{-dyn}	16		95.1	98.5	96.1	94.1	89.1	91.7	76.8
ODDN	20	✓	**95.8**	**98.9**	**97.0**	**95.7**	**91.8**	**93.0**	**80.1**

Table 2: Ablations of how different object representations perform on CLEVRER, all experiments are conducted based on ALOE without self-supervision. "ODDN w/o relation" is ODDN trained without relation module (with only dynamic distillation module). $-dyn$ means reducing distilled dynamic representations (only static representations remained). "MoNet w/o ss" is the result of ALOE without self-supervision from original paper with Monet features.

Baselines. We compare our method with IODINE, PROVIDE and SRVP(Franceschi et al., 2020). IODINE is designed for static images, thus it neither encodes object dynamics nor considers object relations. PROVIDE is an extension of IODINE to fit sequential inputs. The major difference between PROVIDE and our approach is that PROVIDE encodes object dynamics implicitly while we distillate object dynamics explicitly. In detail, PROVIDE uses 2D-LSTM to achieve temporally conditioned and iterative amortized inference for posterior refinement, as a result, the final sampled latents in every time-step contain dynamic information which could be used to predict the future. Besides, PROVIDE does not model object relations, which means when predicting the future, object latents are processed separately. SRVP is a dynamic latent model for stochastic video prediction which decouples frame synthesis and dynamics based on residual updates of a small latent state. Unlike ODDN and PROVIDE, SRVP reperesents the scene with a single latent.

4.1 VIDEO UNDERSTANDING AND REASONING

We study the representation power of ODDN on CLEVRER, which poses different types of questions for each video in CLEVRER dataset. Those questions could test the model's understanding of a video comprehensively, including descriptive questions ("how many objects are moving"), explanatory questions("the reason why certain collision happens"), predictive questions("what will happen next"), and counterfactual questions("what would happen if").

Table 1 shows that ODDN-ALOE outperforms ALOE on all question types even without self-supervision, especially on predictive and counterfactual questions, and achieves state-of-the-art performance. Both predictive and counterfactual types of questions are related to predicting how objects will move. This result proves that representations with object dynamics could help the neural model to do better understanding and reasoning around physical events. We also do ablation experiments to study how different representations affect the model's performance, results are shown in Table 2. We can tell that representations of PROVIDE lead to a significant decline compared to IODINE, and the reason will be discussed in Section. 4.3. On the contrary, representations of ODDN which encode object dynamics (dim=20) outperform IODINE (dim=16) by a large margin, especially on predictive (91.8 vs 84.5) and counterfactual (80.1 vs 73.4) questions. In addition, we obtain ODDN features without dynamics by reducing 4 dimension dynamics. Results show that ODDN without dynamics still performs better than IODINE, which means that ODDN not only distillates useful

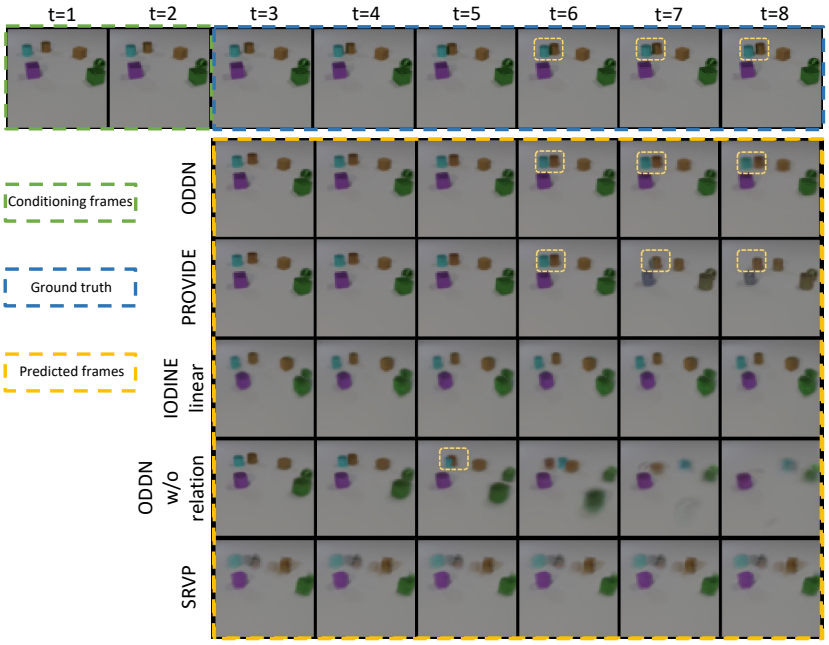

Figure 3: Illustration of video prediction results on CLEVRER. All models take as input the first two frames and predict the next six frames. "IODINE linear" is implemented by simply concatenating latent features of the current and the previous frames and predicting the future frame with a feed-forward neural network. "ODDN w/o relation" is the version of ODDN without relation module. In the video, a collision happens between the blue and brown cylinder from timestep 6 to 8.

object dynamics but also generates better static representations. static representations. "ODDN w/o relation" outperforms "ODDN w/o relation^{-dyn}" which further shows the significance of our distilled object dynamics. However, "DDN w/o relation^{-dyn}" is no better than IODINE (dim=16), which proves that the relation module is the main reason for the quality increase of the object static representation.

4.2 PREDICTION

ODDN achieves predicting future frames in an iterative fashion. Unlike PROVIDE, ODDN models object dynamics and interactions explicitly. Results could be observed in Figure 3, where the blue and brown cylinder collides. ODDN could output reasonable predictions and handle objects collision. PROVIDE could only predict object's future state independently, and the reason is that PROVIDE does not cope with objects interaction, thus, objects blend when they suppose to collide and change their dynamics. ODDN also generates more stable predictions comparing to PROVIDE which fails to capture the object's correct properties (shape, color) after a few frames. "IODINE linear" and SRVP generate identical pictures, which means that both methods are incapable of learning object-level dynamics on CLEVRER. "ODDN w/o relation" learn some dynamics, but the generated results are not reasonable, which may be caused by the training noise: predicting the collision without modeling object interactions. We calculated the average MSE of each of the predicted 6 frames over the entire test set, the quantitative results are shown in Figure 7.

4.3 DECOMPOSITION

Reconstruction. We show how different architectures perform in terms of reconstruction quality in Table 3. Comparing to IODINE, PROVIDE brings some negative effects, as shown in Figure 4. PROVIDE occasionally fails to capture the right object shape. Instead, we notice that ODDN performs better than IODINE. Specifically, the reconstruction of close objects is more precise. We believe that this benefits from the relation module which relies on object surface details to process objects interaction (whether collision occurs and how object dynamics update). The reconstruc-

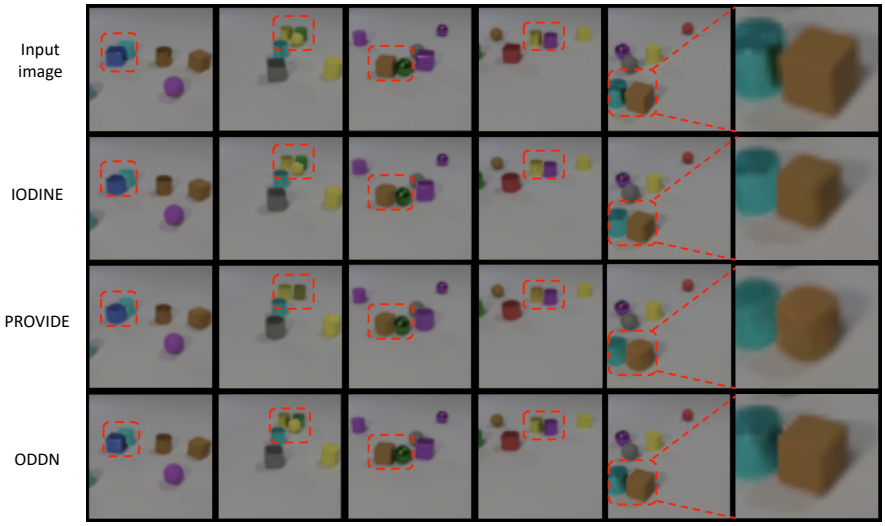

Figure 4: Comparison of reconstruction results of ODDN with IODINE and PROVIDE, we highlight dense areas with dashed boxes.

tion performance is positively correlated to object representation quality which has been verified in Section. 4.1.

Segmentation. ODDN and baseline models decode object latents into pixel values and segmentation masks. The major contribution of PROVIDE is that it models temporal dependencies between latents across frames to obtain better segmentation results.

Table 3: We compare ODDN with baseline models on scene decomposition quality, ODDN* indicates training with the long-range prediction (6 frames).

Model	temporal	MSE ↓	ARI ↑	F-ARI ↑
IODINE		0.000100	0.096	95.55
PROVIDE	✓	0.000148	0.228	95.17
ODDN	✓	**0.000075**	0.156	**95.63**
ODDN*	✓	0.000103	**0.233**	95.36

Table 3 indicates that PROVIDE hurts the model's reconstruction capability. Instead, we show that the future frame prediction task in our architecture also improves the segmentation performance and achieves good reconstruction quality at the same time.

The ARI further improves when increasing the steps of future object states to predict. We believe that the long-range prediction supervision encourages ODDN to attend more on foreground objects which may change its position and view over time. This temporal consistency is similar to PROVIDE, which could be the main reason for both models to achieve better segmentation performance than IODINE. Results are shown in Figure 5.

4.4 Real block towers

Setup. We further evaluate ODDN on the real block tower video dataset(Lerer et al., 2016). The block tower dataset has 493 real-world videos and each video contains a block tower which may or may not be falling. We train models on 393 randomly-selected videos and evaluate them on the rest 100 videos. We study how the models perform in reconstruction and predicting the future frames with the physical concept of "falling".

Results. We show reconstruction results by ODDN and baseline models of images with block towers of different inclination in Figure 6. We found that all models can reconstruct images of stable block towers precisely. However, for blocks with complex spatial position states (e.g., falling with interactions), IODINE and PROVIDE often fail to restore accurate block properties. ODDN performs the best and is able to retain the shape and inclination angle of the object.

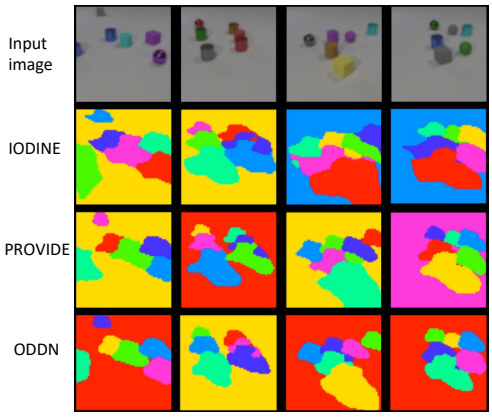

Figure 5: Unsupervised Segmentation results of ODDN, PROVIDE, and IODINE on CLEVRER. Each color corresponds to one slot index whose assignment is unpredictable. Both PROVIDE and ODDN generate better segmentation masks than IODINE.

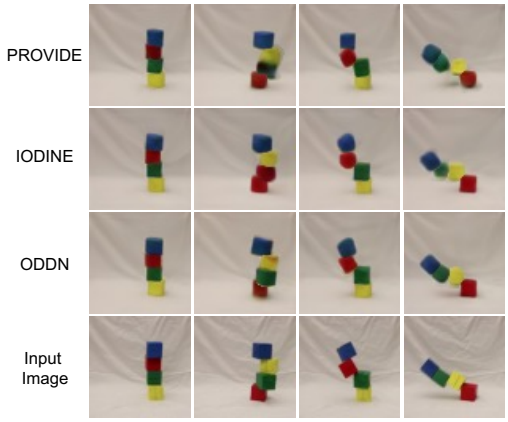

Figure 6: Qualitative comparisons of reconstruction of ODDN with IODINE and with PROVIDE on realistic block towers.

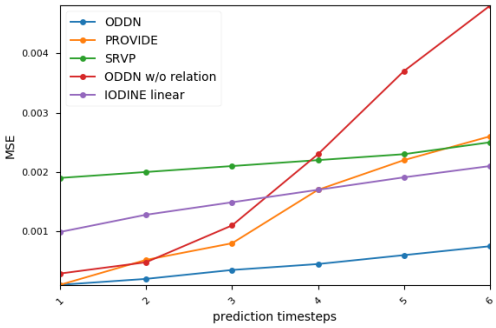

Figure 7: Comparison of MSE for 6 predicted frames of different models on CLEVRER.

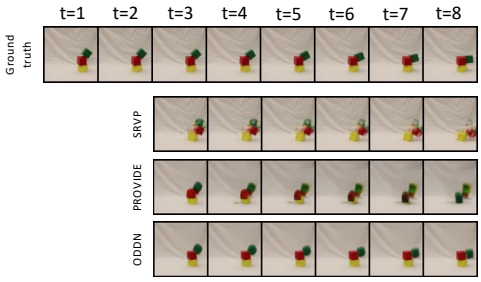

Figure 8: Qualitative comparison of prediction performance of ODDN with PROVIDE and SRVP on realistic block towers.

In Figure 8, we present prediction results of ODDN, PROVIDE and SRVP. SRVP predicts reasonable object dynamics but is not accurate, and the generated images are not clear. The blocks predicted by PROVIDE tend to be blurred and fused over time. ODDN models object interactions, thus predicted blocks do not blend easily.

5 Discussion and Future Work

We presented an unsupervised learning framework ODDN, a novel approach to decompose temporal scene of multiple objects with dynamics and interactions. ODDN distills disentangled object dynamics which are significant in downstream video reasoning task. ODDN also models object interactions which endows the model with the capability of predicting future frames. The incorporating of object dynamics and interactions benefits the model's decomposing ability, reflecting in better segmentation mask and reconstruction quality.

ODDN also has limitations. The prediction quality decrease over time because of the error accumulation. ODDN can only generate deterministic predictions for dynamics obeying regular patterns. Besides, ODDN needs two frames to firstly derive object dynamics then predict the future. However, in the block tower case, humans can tell whether the tower will fall or stay stable with one frame by commonsense. We leave this for future work.

REFERENCES

Vijay Badrinarayanan, Alex Kendall, and Roberto Cipolla. Segnet: A deep convolutional encoder-decoder architecture for image segmentation. *IEEE transactions on pattern analysis and machine intelligence*, 39(12):2481–2495, 2017.

Renee Baillargeon. Object permanence in $31/2$-and $41/2$-month-old infants. *Developmental psychology*, 23(5):655, 1987.

Peter W Battaglia, Jessica B Hamrick, and Joshua B Tenenbaum. Simulation as an engine of physical scene understanding. *Proceedings of the National Academy of Sciences*, 110(45):18327–18332, 2013.

Christopher P Burgess, Loic Matthey, Nicholas Watters, Rishabh Kabra, Irina Higgins, Matt Botvinick, and Alexander Lerchner. Monet: Unsupervised scene decomposition and representation. *arXiv preprint arXiv:1901.11390*, 2019.

Michael B Chang, Tomer Ullman, Antonio Torralba, and Joshua B Tenenbaum. A compositional object-based approach to learning physical dynamics. *arXiv preprint arXiv:1612.00341*, 2016.

Liang-Chieh Chen, George Papandreou, Iasonas Kokkinos, Kevin Murphy, and Alan L Yuille. Deeplab: Semantic image segmentation with deep convolutional nets, atrous convolution, and fully connected crfs. *IEEE transactions on pattern analysis and machine intelligence*, 40(4): 834–848, 2017.

Zhenfang Chen, Jiayuan Mao, Jiajun Wu, Kwan-Yee Kenneth Wong, Joshua B Tenenbaum, and Chuang Gan. Grounding physical concepts of objects and events through dynamic visual reasoning. *arXiv preprint arXiv:2103.16564*, 2021.

Kyunghyun Cho, Bart Van Merriënboer, Caglar Gulcehre, Dzmitry Bahdanau, Fethi Bougares, Holger Schwenk, and Yoshua Bengio. Learning phrase representations using rnn encoder-decoder for statistical machine translation. *arXiv preprint arXiv:1406.1078*, 2014.

David Ding, Felix Hill, Adam Santoro, Malcolm Reynolds, and Matt Botvinick. Attention over learned object embeddings enables complex visual reasoning, 2021.

SM Eslami, Nicolas Heess, Theophane Weber, Yuval Tassa, David Szepesvari, Geoffrey E Hinton, et al. Attend, infer, repeat: Fast scene understanding with generative models. *Advances in Neural Information Processing Systems*, 29:3225–3233, 2016.

Jean-Yves Franceschi, Edouard Delasalles, Mickaël Chen, Sylvain Lamprier, and Patrick Gallinari. Stochastic latent residual video prediction. In *International Conference on Machine Learning*, pp. 3233–3246. PMLR, 2020.

Alex Graves, Santiago Fernández, and Jürgen Schmidhuber. Multi-dimensional recurrent neural networks. In *International conference on artificial neural networks*, pp. 549–558. Springer, 2007.

Klaus Greff, Sjoerd Van Steenkiste, and Jürgen Schmidhuber. Neural expectation maximization. *arXiv preprint arXiv:1708.03498*, 2017.

Klaus Greff, Raphaël Lopez Kaufman, Rishabh Kabra, Nick Watters, Christopher Burgess, Daniel Zoran, Loic Matthey, Matthew Botvinick, and Alexander Lerchner. Multi-object representation learning with iterative variational inference. In *International Conference on Machine Learning*, pp. 2424–2433. PMLR, 2019.

Klaus Greff, Sjoerd van Steenkiste, and Jürgen Schmidhuber. On the binding problem in artificial neural networks. *arXiv preprint arXiv:2012.05208*, 2020.

Sepp Hochreiter and Jürgen Schmidhuber. Long short-term memory. *Neural computation*, 9(8): 1735–1780, 1997.

Jun-Ting Hsieh, Bingbin Liu, De-An Huang, Li Fei-Fei, and Juan Carlos Niebles. Learning to decompose and disentangle representations for video prediction. *arXiv preprint arXiv:1806.04166*, 2018.

Diederik P Kingma and Max Welling. Auto-encoding variational bayes. *arXiv preprint arXiv:1312.6114*, 2013.

Adam R Kosiorek, Hyunjik Kim, Ingmar Posner, and Yee Whye Teh. Sequential attend, infer, repeat: G@inproceedingsgraves2007multi, title=Multi-dimensional recurrent neural networks, author=Graves, Alex and Fernández, Santiago and Schmidhuber, Jürgen, booktitle=International conference on artificial neural networks, pages=549–558, year=2007, organization=Springer enerative modelling of moving objects. *arXiv preprint arXiv:1806.01794*, 2018.

Adam Lerer, Sam Gross, and Rob Fergus. Learning physical intuition of block towers by example. In *International conference on machine learning*, pp. 430–438. PMLR, 2016.

Francesco Locatello, Dirk Weissenborn, Thomas Unterthiner, Aravindh Mahendran, Georg Heigold, Jakob Uszkoreit, Alexey Dosovitskiy, and Thomas Kipf. Object-centric learning with slot attention. *arXiv preprint arXiv:2006.15055*, 2020.

Jonathan Long, Evan Shelhamer, and Trevor Darrell. Fully convolutional networks for semantic segmentation. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pp. 3431–3440, 2015.

William M Rand. Objective criteria for the evaluation of clustering methods. *Journal of the American Statistical association*, 66(336):846–850, 1971.

Olaf Ronneberger, Philipp Fischer, and Thomas Brox. U-net: Convolutional networks for biomedical image segmentation. In *International Conference on Medical image computing and computer-assisted intervention*, pp. 234–241. Springer, 2015.

Sjoerd Van Steenkiste, Michael Chang, Klaus Greff, and Jürgen Schmidhuber. Relational neural expectation maximization: Unsupervised discovery of objects and their interactions. *arXiv preprint arXiv:1802.10353*, 2018.

Sjoerd van Steenkiste, Francesco Locatello, Jürgen Schmidhuber, and Olivier Bachem. Are disentangled representations helpful for abstract visual reasoning? *arXiv preprint arXiv:1905.12506*, 2019.

Marissa A Weis, Kashyap Chitta, Yash Sharma, Wieland Brendel, Matthias Bethge, Andreas Geiger, and Alexander S Ecker. Unmasking the inductive biases of unsupervised object representations for video sequences. *arXiv preprint arXiv:2006.07034*, 2020.

Kexin Yi, Chuang Gan, Yunzhu Li, Pushmeet Kohli, Jiajun Wu, Antonio Torralba, and Joshua B Tenenbaum. Clevrer: Collision events for video representation and reasoning. *arXiv preprint arXiv:1910.01442*, 2019.

Polina Zablotskaia, Edoardo A Dominici, Leonid Sigal, and Andreas M Lehrmann. Unsupervised video decomposition using spatio-temporal iterative inference. *arXiv preprint arXiv:2006.14727*, 2020.

A DETAINS ON METHOD AND IMPLEMENTATION

A.1 ALGORITHM

Here we detail our algorithm with pseudocode:

Algorithm 1 ODDN Pseudocode

Input: video $x_1 \dots x_N$, hyperparamters K, T
Input: trainable parameters $\lambda^{(1)}$, θ, ϕ, ρ, δ, σ
Initialization: $h_k^{(1)} \overset{k}{\longleftarrow} 0$
Function $InferReconstruct(x)$:
  for $t = 1$ **to** T **do**
    $z_k^{(t)} \overset{k}{\sim} q_\lambda(z_k^{(t)}|x)$
    $\mu_k^{(t)}, \hat{m}_k^{(t)} \overset{k}{\longleftarrow} Decoder_\theta(z_k^{(t)})$
    $m^(t) \longleftarrow softmax_k(\hat{m}_k^{(t)})$
    $p(x|z^{(t)}) \longleftarrow \sum_k m_k^{(t)} \mathcal{N}(x; \mu_k^{(t)}, \sigma^2)$
    $\mathcal{L}_r^{(t)}(x) \longleftarrow D_{KL}(q_\lambda(z^{(t)}|x)||p(z)) - \beta log(p(x|z^{(t)}))$
    $a_k \overset{k}{\longleftarrow}$ inputs$(x, z_k^{(t)}, \lambda_k^{(t)})$
    $\lambda_k^{(t+1)}, h^(t+1) \overset{k}{\longleftarrow} f_\phi(a_k, h_k^{(t)})$
  end for
for $n = 1$ **to** $N - 2$ **do**
  $z_{n\cdot}, \mathcal{L}_r(x_n) \longleftarrow InferReconstruct(x_n)$
  $z_{(n+1)\cdot}, \mathcal{L}_r(x_{n+1}) \longleftarrow InferReconstruct(x_{n+1})$
  $dyn_{(n+1)\cdot} \longleftarrow Transformer_\rho(z_{n\cdot}, z_{(n+1)\cdot})$
  $dyn'_{(n+1)\cdot} \longleftarrow Relation_\delta(dyn_{(n+1)\cdot}, z_{(n+1)\cdot})$
  $\hat{z}_{(n+2)k} \overset{k}{\longleftarrow} Predictor_\sigma(dyn'_{(n+1)k}, z_{(n+1)k})$
  $\mathcal{L}_p(x_{(n+2)}) \longleftarrow -log(p(x_{(n+2)}|\hat{z}_{(n+2)}))$

A.2 DATASET

CLEVRER is a synthetic video dataset of moving and colliding objects. Each video contains 128 frames at resolution 480 $\times$ 320. We pre-train ODDN on the entire CLEVRER training set, in order to promote convergence of our Relation Module, we extract images every 4 frames and ensure that at least one collision event is included forming CLEVRER-collision and we finetune ODDN on CLEVRER-collision. For testing, we use the validation set which has ground truth masks, we sample 1k sub-clips containing 6 objects, each sub-clip consists of 10 frames.

A.3 HYPER-PARAMETERS

We Generally follow the setting of PROVIDE. We initialize the parameters of the posterior λ by sampling from $\mathcal{U}(-0.5, 0.5)$. In experiments in prediction tasks, we use a latent dimensionality dim(z) = 64 and downscals the image into 64$\times$64 after a center-crop preprocess as IODINE and PROVIDE, such that dim(λ) = 128. And in experiments in video resoning task, we use a latent dimensionality dim(z) = 16 as ALOE which makes dim(λ) = 32, and downscals the image into 64$\times$96 without crop. The variance of the likelihood is set to σ = 0.3 in all experiments. We keep the default number of iterative refinements at R = 5, and use K = 7 slots for both training and testing. Furthermore, we set β = 100.0 for all experiments.

A.4 TRAINING

We train our models on 8 GeForce RTX 3090 GPUs, which takes approximately two days per model. We use ADAM for all experiments, with a learning rate of 0.0003 and default values for all remaining parameters. During training, we gradually increase the number of frames per video, as

we have found this to make the optimisation more stable. We train models with sequences of length 8 and the batch size is 12.

B MODEL COMPUTATIONAL COMPLEXITY

Table 4: Computational complexity comparison between ODDN and IODINE and PROVIDE.

Model	GFLOPs	params	model size (Mb)
IODINE	17.2187	2780052	10.61
PROVIDE	17.2251	2977940	11.36
ODDN	17.2189	2925365	11.16

C MORE VISUALIZATION RESULTS

C.1 COMPONENT VISUALIZATION

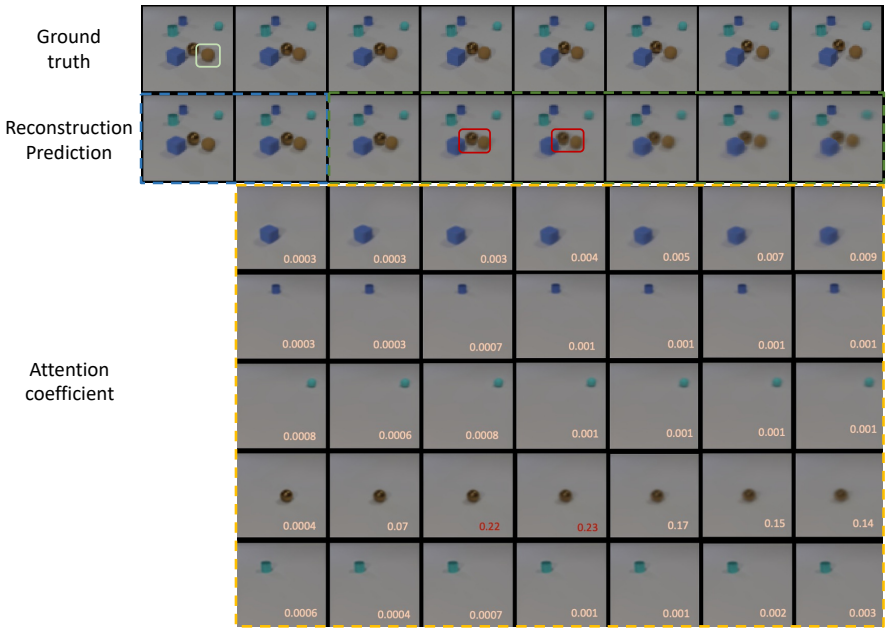

Figure 9: Addition prediction results of ODDN on CLEVRER and detailed attention coefficients visualization for relation module. We plot attention the scores all objects have on the rubber sphere from the second frame. The collision happens between the rubber sphere and the metal sphere.

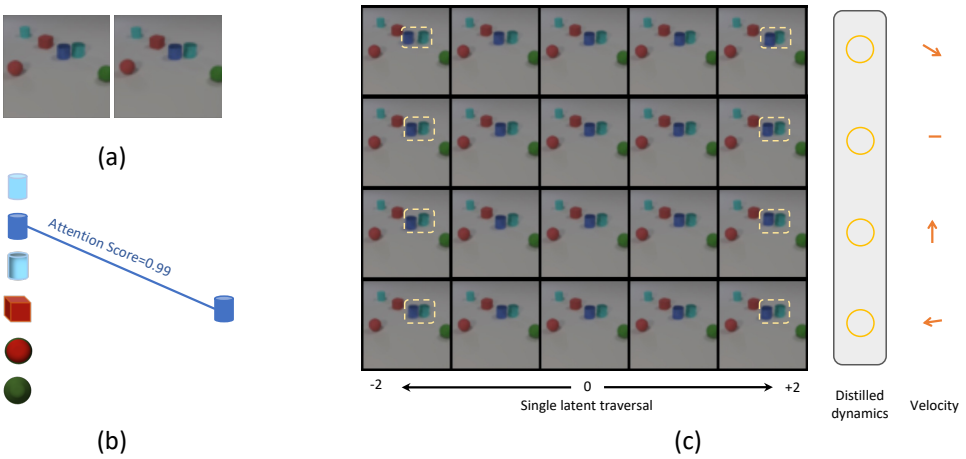

Figure 10: (a) Two consecutive frames with only the blue cylinder moving. (b) Visualization of the Transformer attention map of the blue cylinder in the matching phase of dynamics distillation. Latents of the second frame will update its representations by attending and merge information from latents of the first frame. Line intensity indicates the magnitude of attention probability. (c) Disentanglement visualization of the learned object dynamics. We adjust the feature value (from -2 to 2) of the corresponding dynamic representation dimension of the blue cylinder, and visualize the effects on the predicted next frame. We use arrows to show the velocity direction each dimension represents.