

Object-driven Text-to-Image Synthesis via Adversarial Training

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Abstract

In this paper, we propose *Object-driven Attentive Generative Adversarial Networks (Obj-GANs)* that allow object-centered text-to-image synthesis for complex scenes. Following the two-step (layout-image) generation process, a novel object-driven attentive image generator is proposed to synthesize salient objects by paying attention to the most relevant words in the text description and the pre-generated semantic layout. In addition, a new Fast R-CNN based object-wise discriminator is proposed to provide rich object-wise discrimination signals on whether the synthesized object matches the text description and the pre-generated layout. The proposed Obj-GAN significantly outperforms the previous state of the art in various metrics on the large-scale COCO benchmark, increasing the Inception score by 27% and decreasing the FID score by 11%. A thorough comparison between the traditional grid attention and the new object-driven attention is provided through analyzing their mechanisms and visualizing their attention layers, showing insights of how the proposed model generates complex scenes in high quality.

1. Introduction

Synthesizing images from text descriptions (known as *Text-to-Image synthesis*) is an important machine learning task, which requires handling ambiguous and incomplete information in natural language descriptions and learning across vision and language modalities. Approaches based on Generative Adversarial Networks (GANs) [5] have recently achieved promising results on this task [23, 22, 32, 33, 29, 16, 9, 12, 34]. Most GAN based methods synthesize the image conditioned only on a global sentence vector, which may miss important fine-grained information at the word level, and prevents the generation of high-quality images. More recently, AttnGAN [29] is proposed which introduces the attention mechanism [28, 30, 2, 27] into the GAN framework, thus allows attention-driven, multi-stage

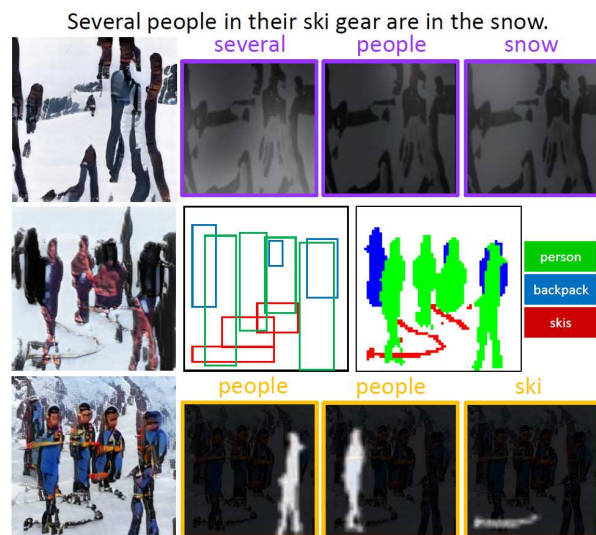


Figure 1: Top: AttnGAN [29] and its grid attention visualization. Middle: our modified implementation of two-step (layout-image) generation proposed in [9]. Bottom: our Obj-GAN and its object-driven attention visualization. The middle and bottom generations use the same *generated* semantic layout, and the only difference is the object-driven attention.

refinement for fine-grained text-to-image generation.

Although images with realistic texture have been synthesized on simple datasets, such as birds [29, 16] and flowers [33], most existing approaches do not specifically model objects and their relations in images and thus have difficulties in generating complex scenes such as those in the COCO dataset [15]. For example, generating images from a sentence “several people in their ski gear are in the snow” requires modeling of different objects (people, ski gear) and their interactions (people on top of ski gear), as well as filling the missing information (*e.g.*, the rocks in the background). In the top row of Fig. 1, the image generated by AttnGAN does contain scattered texture of people and snow, but the shape of people are distorted and the picture’s layout is semantically not meaningful. [9] remedies this problem by first constructing a semantic layout from the text and then synthesizing the image by a deconvolutional

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image generator. However, the fine-grained word/object-level information is still not explicitly used for generation. Thus, the synthesized images do not contain enough details to make them look realistic (see the middle row of Fig. 1).

In this study, we aim to generate high-quality complex images with semantically meaningful layout and realistic objects. To this end, we propose a novel Object-driven Attentive Generative Adversarial Networks (Obj-GAN) that effectively capture and utilize fine-grained word/object-level information for text-to-image synthesis. The Obj-GAN consists of a pair of object-driven attentive image generator and object-wise discriminator, and a new object-driven attention mechanism. The proposed image generator takes as input the text description and a pre-generated semantic layout and synthesize high-resolution images via a multiple-stage coarse-to-fine process. At *every* stage, the generator synthesizes the image region within a bounding box by focusing on words that are most relevant to the object in that bounding box, as illustrated in the bottom row of Fig. 1. More specifically, using a new object-driven attention layer, it uses the class label to query words in the sentences to form a word context vector, as illustrated in Fig. 4, and then synthesizes the image region conditioned on the class label and word context vector. The object-wise discriminator checks every bounding box to make sure that the generated object indeed matches the pre-generated semantic layout. To compute the discrimination losses for all bounding boxes simultaneously and efficiently, our object-wise discriminator is based on a Fast R-CNN [4], with a binary cross-entropy loss for each bounding box.

The contribution of this work is three-folded. (i) An Object-driven Attentive Generative Network (Obj-GAN) is proposed for synthesizing complex images from text descriptions. Specifically, two novel components are proposed, including the object-driven attentive generative network and the object-wise discriminator. (ii) Comprehensive evaluation on a large-scale COCO benchmark shows that our Obj-GAN significantly outperforms previous state-of-the-art text-to-image synthesis methods. Detailed ablation study is performed to empirically evaluate the effect of different components in Obj-GAN. (iii) A thorough analysis is performed through visualizing the attention layers of the Obj-GAN, showing insights of how the proposed model generates complex scenes in high quality. Compared with the previous work, our object-driven attention is more robust and interpretable, and significantly improves the object generation quality in complex scenes.

2. Related Work

Generating photo-realistic images from text descriptions, though challenging, is important to many real-world applications such as art generation and computer-aided design. There has been much research effort for this task

through different approaches, such as variational inference [17, 6], approximate Langevin process [24], conditional PixelCNN via maximal likelihood estimation [26, 24], and conditional generative adversarial networks [23, 22, 32, 33]. Compared with other approaches, Generative Adversarial Networks (GANs) [5] have shown better performance in image generation [21, 3, 25, 13, 11, 10]. However, existing GAN based text-to-image synthesis is usually conditioned only on the global sentence vector, which misses important fine-grained information at the word level, and thus lacks the ability to generate high-quality images. [29] uses the traditional grid visual attention mechanism in this task, which enables synthesizing fine-grained details at different image regions by paying attentions to the relevant words in the text description.

To explicitly encode the semantic layout into the generator, [9] proposes to decompose the generation process into two steps, in which it first constructs a semantic layout (bounding boxes and object shapes) from the text and then synthesizes an image conditioned on the layout and text description. [12] also proposes such a two-step process to generate images from scene graphs, and their process can be trained end-to-end. In this work, the proposed Obj-GAN follows the two-step generation process as [9]. However, [9] encodes the text into a single global sentence vector, which loses word-level fine-grained information. Moreover, it uses the image-level GAN loss for the discriminator, which is less effective at providing object-wise discrimination signal for generating salient objects. We propose a new object-driven attention mechanism to provide fine-grained information (words in the text description and objects in the layout) for different components, including an attentive seq2seq bounding box generator, an attentive image generator and an object-wise discriminator.

The attention mechanism has recently become a crucial part of vision-language multi-modal intelligence tasks. The traditional grid attention mechanism has been successfully used in modeling multi-level dependencies in image captioning [28], image question answering [30], text-to-image generation [29], unconditional image synthesis [31] and image-to-image translation [16], image/text retrieval [14]. In 2018, [1] proposes a bottom-up attention mechanism, which enables attention to be calculated over semantic meaningful regions/objects in the image, for image captioning and visual question-answering. Inspired by these works, we propose Obj-GAN which for the first time develops an object-driven attentive generator plus an object-wise discriminator, thus enables GANs to synthesize high-quality images of complicated scenes.

3. Object-driven Attentive GAN

As illustrated in Fig. 2, the Obj-GAN performs text-to-image synthesis in two steps: generating a semantic lay-

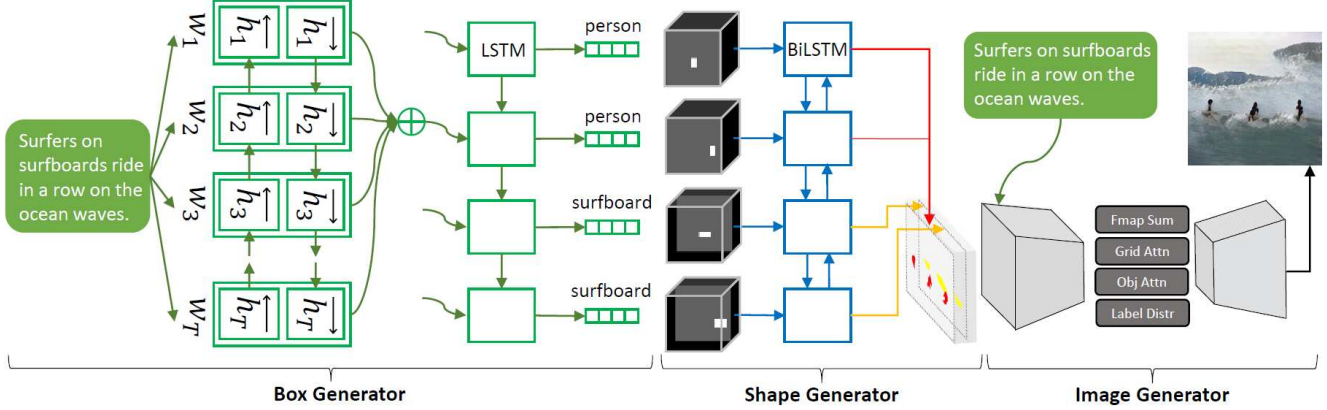


Figure 2: Obj-GAN completes the text-to-image synthesis in two steps: the layout generation and the image generation. The layout generation contains a bounding box generator and a shape generator. The image generation uses the object-driven attentive image generator.

out (class labels, bounding boxes, shapes of salient objects), and then generating the image. In the image generation step, the object-driven attentive generator and object-wise discriminator are designed to enable image generation conditioned on the semantic layout generated in the first step.

The input of Obj-GAN is a sentence with T_s tokens. With a pre-trained bi-LSTM model, we encode its words as word vectors $e \in \mathbb{R}^{D \times T_s}$ and the entire sentence as a global sentence vector $\bar{e} \in \mathbb{R}^D$. We provide details of this pre-trained bi-LSTM model and the implementation details of other modules of Obj-GAN in § ??.

3.1. Semantic layout generation

In the first step, the Obj-GAN takes the sentence as input and generates a semantic layout, a sequence of objects specified by their bounding boxes (with class labels) and shapes. As illustrated in Fig. 2, a box generator first generates a sequence of bounding boxes, and then a shape generator generates their shapes. This part resembles the bounding box generator and shape generator in [9], and we put our implementation details in § ??.

Box generator. We train an attentive seq2seq model [2], also referring to Fig. 2, as the box generator:

$$B_{1:T} := [B_1, B_2, \dots, B_T] \sim G_{\text{box}}(e). \quad (1)$$

Here, e are the pre-trained bi-LSTM word vectors, $B_t = (l_t, b_t)$ are the class label of the t 's object and its bounding box $b = (x, y, w, h) \in \mathbb{R}^4$. In the rest of the paper, we will also call the label-box pair B_t as a bounding box when no confusion arises. Since most of the bounding boxes have corresponding words in the sentence, the attentive seq2seq model captures this correspondence better than the seq2seq model used in [9].

Shape generator. Given the bounding boxes $B_{1:T}$, the shape generator predicts the shape of each object in its bounding box, i.e.,

$$\hat{M}_{1:T} = G_{\text{shape}}(B_{1:T}, z_{1:T}). \quad (2)$$

where $z_t \sim \mathcal{N}(0, 1)$ is a random noise vector. Since the generated shapes not only need to match the location and category information provided by $B_{1:T}$, but also should be aligned with its surrounding context, we build G_{shape} based on a bi-directional convolutional LSTM, as illustrated in Fig. 2. Training of G_{shape} is based on the GAN framework [9], in which a perceptual loss is also used to constrain the generated shapes and to stabilize the training.

3.2. Image generation

3.2.1 Attentive multistage image generator

As shown in Fig. 3, the proposed attentive multistage generative network has two generators (G_0, G_1). The base generator G_0 first generates a low-resolution image \hat{x}_0 conditioned on the global sentence vector and the pre-generated semantic layout. The refiner G_1 then refines details in different regions by paying attention to most relevant words and pre-generated class labels and generates a higher resolution image \hat{x}_1 . Specifically,

$$h_0 = F_0(z, \bar{e}, \text{Enc}(M^0), c^{\text{obj}}, c^{\text{lab}}), \quad \hat{x}_0 = G_0(h_0),$$

$$h_1 = F_1(c^{\text{pat}}, h_0 + \text{Enc}(M^1), c^{\text{obj}}, c^{\text{lab}}), \quad \hat{x}_1 = G_1(h_1),$$

where (i) z is a random vector with standard normal distribution; (ii) $\text{Enc}(M^0)$ ($\text{Enc}(M^1)$) is the encoding of low-resolution shapes M^0 (higher-resolution shapes M^1); (iii) $c^{\text{pat}} = F_{\text{attn}}^{\text{grid}}(e, h_0)$ are the patch-wise context vectors from the traditional grid attention, (iv) $c^{\text{obj}} = F_{\text{attn}}^{\text{obj}}(e, e^g, l^g, M)$ are the object-wise context vectors from our new object-driven attention, and $c^{\text{lab}} = c^{\text{lab}}(l^g, M)$ are the label context vectors from class labels. We can stack more refiners to the generation process and get higher and higher resolution images. In this paper, we have two refiners (G_1 and G_2) and finally generate images with resolution 256×256 .

Compute context vectors via attention. Both patch-wise context vectors c^{pat} and object-wise context vectors c^{obj} are attention-driven context vectors for specific image regions, and encode information from the words that are most relevant to that image region. Patch-wise context vectors are

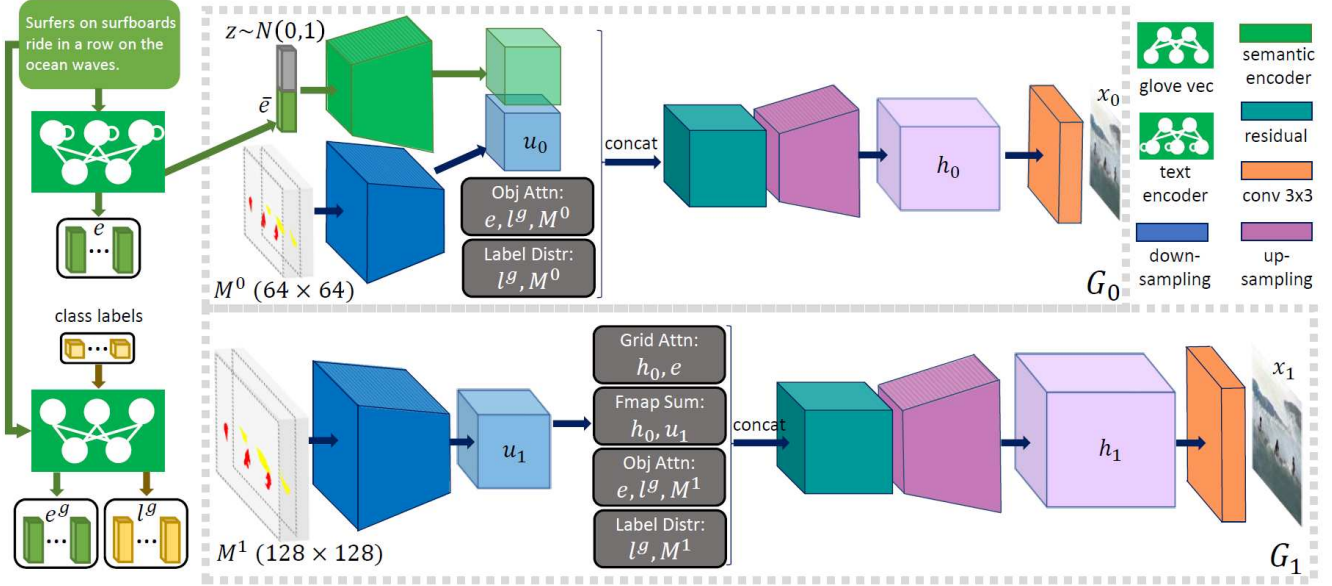


Figure 3: The object-driven attentive image generator.

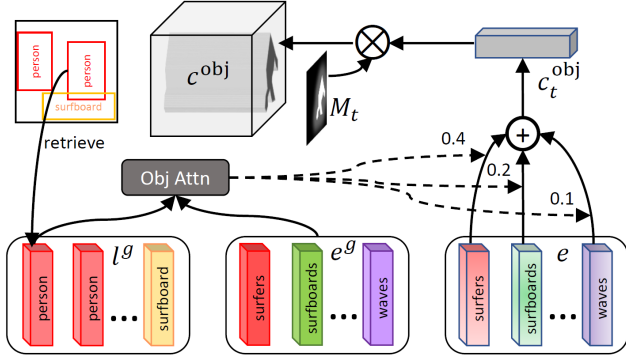


Figure 4: Object-driven attention.

for uniform-partitioned image patches determined by the uniform down-sampling/up-sampling structure of CNN, but these patches are not semantically meaningful. Object-wise context vectors are for semantically meaningful image regions specified by bounding boxes, but these regions are at different scales and may have overlaps.

Specifically, the patch-wise context vector c_j^{pat} (objective-wise context vector c_t^{obj}) is a dynamic representation of word vectors relevant to patch j (bounding box B_t), which is calculated by

$$c_j^{\text{pat}} = \sum_{i=1}^{T_s} \beta_{j,i}^{\text{pat}} e_i, \quad c_t^{\text{obj}} = \sum_{i=1}^{T_s} \beta_{t,i}^{\text{obj}} e_i. \quad (3)$$

Here, $\beta_{j,i}^{\text{pat}}$ ($\beta_{t,i}^{\text{obj}}$) indicates the weight the model attends to the i 'th word when generating patch j (bounding box B_t) and is computed by

$$\beta_{j,i}^{\text{pat}} = \frac{\exp(s_{j,i}^{\text{pat}})}{\sum_{k=1}^{T_s} \exp(s_{j,k}^{\text{pat}})}, \quad s_{j,i}^{\text{pat}} = (h_j)^T e_i, \quad (4)$$

$$\beta_{t,i}^{\text{obj}} = \frac{\exp(s_{t,i}^{\text{obj}})}{\sum_{k=1}^{T_s} \exp(s_{t,k}^{\text{obj}})}, \quad s_{t,i}^{\text{obj}} = (l_t^g)^T e_i^g. \quad (5)$$

For the traditional grid attention, we use the image region feature h_j , which is one column in the previous hidden layer $h \in \mathbb{R}^{D^{\text{pat}} \times N^{\text{pat}}}$, to query the pre-trained bi-LSTM word vectors e . For the new object-driven attention, we use the GloVe embedding of object class label l_t^g to query the GloVe embedding of the words in the sentence, as illustrated in the lower part of Fig. 4.

Feature map concatenation. The patch-wise context vector c_j^{pat} can be directly concatenated with the image feature vector h_j in the previous layer. However, the object-wise context vector c_t^{obj} cannot, because they are associated with bounding boxes instead of pixels in the hidden feature map. We propose to copy the object-wise context vector c_t^{obj} to every pixel where the t 'th object is present, i.e., $M_t \otimes c_t^{\text{obj}}$ where \otimes is the vector outer-product, as illustrated in the upper-right part of Fig. 4.¹

If there are multiple bounding boxes covering the same pixel, we have to decide whose context vector should be used on this pixel. In this case, we simply do a max-pooling across all the bounding boxes:

$$c^{\text{obj}} = \max_{t: 1 \leq t \leq T} M_t \otimes c_t^{\text{obj}}. \quad (6)$$

Then c^{obj} can be concatenated with the feature map h and patch-wise context vectors c^{pat} for next-stage generation.

Label context vectors. Similarly, we distribute the class label information to the entire hidden feature map to get the label context vectors, i.e.,

$$c^{\text{lab}} = \max_{t: 1 \leq t \leq T} M_t \otimes e_t^g. \quad (7)$$

Finally, we concatenate h , c^{pat} , c^{obj} and c^{lab} and pass the

¹This operation can be viewed as an inverse of the pooling operator.

concatenated tensor through one up-sampling layer and several residual layers to generate a higher-resolution image.

Grid attention vs. object-driven attention. The process to compute the patch-wise context vectors above is the traditional grid attention mechanism used in AttnGAN [29]. Note that its attention weights $\beta_{j,i}^{\text{pat}}$ and context vector c_j^{pat} are useful only when the hidden feature h_j^{pat} in the G_0 stage correctly captures the content to be drawn in patch j . This essentially assumes that the generation in the G_0 stage already captures a rough sketch (semantic layout). This assumption is valid for simple datasets like birds [29], but fails for complex datasets like COCO [15] where the generated low-resolution image \hat{x}_0 typically does *not* have a meaningful layout. In this case, the grid attention is even harmful, because patch-wise context vector is attended to a wrong word and thus generate the texture associated with that wrong word. This may be the reason why AttnGAN’s generated image contains scattered patches of realistic texture but overall is semantically not meaningful; see Fig. 1 for example. Similar phenomenon is also observed in DeepDream [20]. On the contrary, in our object-driven attention, the attention weights $\beta_{t,i}^{\text{obj}}$ and context vector c_t^{obj} rely on the class label l_t^g of the bounding box and are independent of the generation in the G_0 stage. Therefore, the object-wise context vectors are always helpful to generate images that are consistent with the pre-generated semantic layout. Another benefit of this design is that the context vector c_t^{obj} can also be used in the discriminator, as we present in § 3.2.2.

3.2.2 Discriminators

We design patch-wise and object-wise discriminators to train the attentive multi-stage generator above. Given a patch from uniformly-partitioned image patches determined by the uniform down-sampling structure of CNN, the patch-wise discriminator is trying to determine whether this patch is realistic or not (unconditional) and whether this patch is consistent with the sentence description or not (conditional). Given a bounding box and the class label of the object within it, the object-wise discriminator is trying to determine whether this region is realistic or not (unconditional) and whether this region is consistent with the sentence description and given class label or not (conditional).

Patch-wise discriminators. Given an image-sentence pair x, \bar{e} (\bar{e} is the sentence vector), the patch-wise unconditional and text discriminator can be written as

$$p^{\text{pat,un}} = D_{\text{uncond.}}^{\text{pat}}(\text{Enc}(x)), \quad p^{\text{pat,con}} = D_{\text{text}}^{\text{pat}}(\text{Enc}(x), \bar{e}), \quad (8)$$

where Enc is a convolutional feature extractor that extracts patch-wise features, $D_{\text{uncond.}}$ (D_{text}) determine whether the patch is realistic (consistent with the text description) or not.

Shape discriminator. In a similar manner, we have our patch-wise shape discriminator

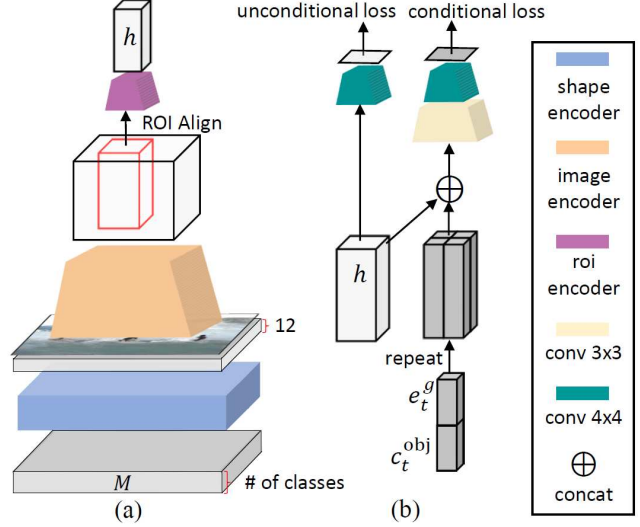


Figure 5: Object-wise discriminator.

$$p^{\text{pix}} = D^{\text{pix}}(\text{Enc}(x, M)), \quad (9)$$

where we first concatenate the image x and shapes M in the channel dimension, and then extracts patch-wise features by another convolutional feature extractor Enc . The probabilities p^{pix} determine whether the patch is consistent with the given shape. Our patch-wise discriminators $D_{\text{uncond.}}^{\text{pat}}$, $D_{\text{text}}^{\text{pat}}$ and D^{pix} resembles the PatchGAN [11] for the image-to-image translation task. Compared with the global discriminators in AttnGAN [29], the patch-wise discriminators not only reduce the model size and thus enable generating higher resolution images, but also increase the quality of generated images; see Table 1 for experimental evidence.

Object-wise discriminators. Given an image x , bounding boxes of objects $B_{1:T}$ and their shapes M , we propose the following object-wise discriminators:

$$\{h_t^{\text{obj}}\}_{t=1}^T = \text{FastRCNN}(x, M, B_{1:T}), \\ p_t^{\text{obj,un}} = D_{\text{uncond.}}^{\text{obj}}(h_t^{\text{obj}}), \quad p_t^{\text{obj,con}} = D_{\text{con}}^{\text{obj}}(h_t^{\text{obj}}, e_t^g, c_t^{\text{obj}}). \quad (10)$$

Here, we first concatenate the image x and shapes M and extract a region feature vector h_t^{obj} for each bounding box through a Fast R-CNN model [4] with an ROI-align layer [7]; see Fig. 5(a). Then similar to the patch-wise discriminator (8), the unconditional (conditional) probabilities $p_t^{\text{obj,un}}$ ($p_t^{\text{obj,con}}$) determine whether the t ’th object is realistic (consistent with its class label e_t^g and its text context information c_t^{obj}) or not; see Fig. 5(b). Here, e_t^g is the GloVe embedding of the class label and c_t^{obj} is its text context information defined in (3).

All discriminators are trained by the traditional cross entropy loss [5].

3.2.3 Loss function for the image generator

The generator’s GAN loss is a weighted sum of these discriminators’ loss, *i.e.*,

$$\mathcal{L}_{\text{GAN}}(G) = -\frac{\lambda_{\text{obj}}}{T} \sum_{t=1}^T \left(\underbrace{\log p_t^{\text{obj,un}}}_{\text{obj uncond. loss}} + \underbrace{\log p_t^{\text{obj,con}}}_{\text{obj cond. loss}} \right) - \frac{1}{N^{\text{pat}}} \sum_{j=1}^{N^{\text{pat}}} \left(\underbrace{\log p_j^{\text{pat,un}}}_{\text{uncond. loss}} + \underbrace{\lambda_{\text{txt}} \log p_j^{\text{pat,con}}}_{\text{text cond. loss}} + \underbrace{\lambda_{\text{pix}} \log p_j^{\text{pix}}}_{\text{shape cond. loss}} \right).$$

Here, T is the number of bounding boxes, N^{pat} is the number of regular patches, $(\lambda_{\text{obj}}, \lambda_{\text{txt}}, \lambda_{\text{pix}})$ are the weights of the object-wise GAN loss, patch-wise text conditional loss and patch-wise shape conditional loss, respectively. We tried combining our discriminators with the spectral normalized projection discriminator [18, 19], but did not see significant performance improvement. We report performance of the spectral normalized version in § 4.1 and provide model architecture details in § ??.

Combined with the deep multi-modal attentive similarity model (DAMSM) loss introduced in [29], our final image generator’s loss is

$$\mathcal{L}_G = \mathcal{L}_{\text{GAN}} + \lambda_{\text{DAMSM}} \mathcal{L}_{\text{DAMSM}} \quad (11)$$

where λ_{damsm} is a hyper-parameter to be tuned. Here, the DAMSM loss is a word level fine-grained image-text matching loss computed, which will be elaborated in § ??. Based on the experiments on a held-out validation set, we set the hyperparameters in this section as: $\lambda_{\text{obj}} = 0.1$, $\lambda_{\text{txt}} = 0.1$, $\lambda_{\text{pix}} = 1$ and $\lambda_{\text{damsm}} = 100$.

Remark 3.1. *Both the patch-wise and object-wise discriminators can be applied to different stages in the generation. We apply the patch-wise discriminator for every stage of the generation, following [33, 11], but only apply the object-wise discriminator at the final stage.*

4. Experiments

Dataset. We use the COCO dataset [15] for evaluation. It contains 80 object classes, where each image is associated with object-wise annotations (*i.e.*, bounding boxes and shapes) and 5 text descriptions. We use the official 2014 train (over 80K images) and validation (over 40K images) splits for training and test stages, respectively.

Evaluation metrics. We use the Inception score [25] and Fréchet inception distance (FID) [8] score as the quantitative evaluation metrics. In our experiments, we found that Inception score can be saturated, even over-fitted, while FID is a more robust measure and aligns better with human qualitative evaluation. Following [29], we also use R-precision,

Table 1: The quantitative experiments. Methods marked with 0, 1 and 2 respectively represent experiments using the predicted boxes and shapes, the ground-truth boxes and predicted shapes, and the ground-truth boxes and shapes. We use **bold**, *, and ** to highlight the best performance under these three settings, respectively. The results of methods marked with † are those reported in the original papers. † (‡) means the higher (lower), the better.

Methods	Inception †	FID ‡	R-prcn (%) †
Obj-GAN ⁰	27.37 ± 0.22	25.85	86.20 ± 2.98
Obj-GAN ¹	27.96 ± 0.39*	24.19*	88.36 ± 2.82
Obj-GAN ²	29.89 ± 0.22**	20.75**	89.59 ± 2.67
P-AttnGAN w/ Lyt ⁰	18.84 ± 0.29	59.02	65.71 ± 3.74
P-AttnGAN w/ Lyt ¹	19.32 ± 0.29	54.96	68.40 ± 3.79
P-AttnGAN w/ Lyt ²	20.81 ± 0.16	48.47	70.94 ± 3.70
P-AttnGAN	26.31 ± 0.43	41.51	86.71 ± 2.97
Obj-GAN w/ SN ⁰	26.97 ± 0.31	29.07	86.84 ± 2.82
Obj-GAN w/ SN ¹	27.41 ± 0.17	27.26	88.70 ± 2.65*
Obj-GAN w/ SN ²	28.75 ± 0.32	23.37	89.97 ± 2.56**
Reed <i>et al.</i> [23]†	7.88 ± 0.07	n/a	n/a
StackGAN [32]†	8.45 ± 0.03	n/a	n/a
AttnGAN [29]	23.79 ± 0.32	28.76	82.98 ± 3.15
vmGAN [35]†	9.94 ± 0.12	n/a	n/a
Sg2Im [12]†	6.7 ± 0.1	n/a	n/a
Infer [9] ⁰ †	11.46 ± 0.09	n/a	n/a
Infer [9] ¹ †	11.94 ± 0.09	n/a	n/a
Infer [9] ² †	12.40 ± 0.08	n/a	n/a
Obj-GAN-SOTA ⁰	30.29 ± 0.33	25.64	91.05 ± 2.34
Obj-GAN-SOTA ¹	30.91 ± 0.29	24.28	92.54 ± 2.16
Obj-GAN-SOTA ²	32.79 ± 0.21	21.21	93.39 ± 2.08

a common evaluation metric for ranking retrieval results, to evaluate whether the generated image is well conditioned on the given text description. More specifically, given a pre-trained image-to-text retrieval model, we use generated images to query their corresponding text descriptions. First, given generated image \hat{x} conditioned on sentence s and 99 random sampled sentences $\{s'_i : 1 \leq i \leq 99\}$, we rank these 100 sentences by the pre-trained image-to-text retrieval model. If the ground truth sentence s is ranked highest, we count this a success retrieval. For all the images in the test dataset, we perform this retrieval task once and finally count the percentage of success retrievals as the R-precision score.

It is important to point out that none of these quantitative metrics are perfect. Better metrics are required to evaluate image generation qualities in complicated scenes. In fact, the Inception score completely fails in evaluating the semantic layout of the generated images. The R-precision score depends on the pre-trained image-to-text retrieval model it uses, and can only capture the aspects that the retrieval model is able to capture. The pre-trained model we use is still limited in capturing the relations between objects in complicated scenes, so is our R-precision score.

Quantitative evaluation. We compute these three metrics under two settings for the full validation dataset.

Qualitative evaluation. Apart from the quantitative evaluation, we also visualize the outputs of all ablative versions of Obj-GAN and the state-of-the-art methods (*i.e.*, [29]) whose pre-trained models are publicly available.



Figure 6: The overall qualitative comparison. All images are generated without the usage of any ground-truth information.

4.1. Ablation study

In this section, we first evaluate the effectiveness of the object-driven attention. Next, we compare the object-driven attention mechanism with the grid attention mechanism. Then, we evaluate the impact of the spectral normalization for Obj-GAN. We use Fig. 6 and the higher half of Table 1 to present the comparison among different ablative versions of Obj-GAN. Note that all ablative versions have been trained with batch size 16 for 60 epochs. In addition, we use the lower half of Table 1 to show the comparison between Obj-GAN and previous methods. Finally, we validated the Obj-GAN’s generalization ability on the novel text descriptions.

Object-driven attention. To evaluate the efficacy of the object-driven attention mechanism, we implement a baseline, named P-AttnGAN w/ Lyt, by disabling the object-driven attention mechanism in Obj-GAN. In essence, P-AttnGAN w/ Lyt can be considered as an improved version of AttnGAN with the patch-wise discriminator (abbreviated as the prefix “P-” in name) and the modules (e.g., shape discriminator) for handling the conditional layout (abbreviated as “Lyt”). Moreover, it can also be considered as a modified implementation of [9], which resembles their two-step (layout-image) generation. Note that there are three key differences between P-AttnGAN w/ Lyt and [9]: (i) P-AttnGAN w/ Lyt has a multi-stage image generator that gradually increases the generated resolution and refines the generated images, while [9] has a single-stage image generator. (ii) With the help of the grid attentive module, P-AttnGAN w/ Lyt is able to utilize the fine-grained word-level information, while [9] conditions on the global sentence information. (iii) The third difference lies in their loss

functions: P-AttnGAN w/ Lyt uses the DAMSM loss in (11) to penalize the mismatch between the generated images and the input text descriptions, while [9] uses the perceptual loss to penalize the mismatch between the generated images and the ground-truth images. As shown in Table 1, P-AttnGAN w/ Lyt yields higher Inception score than [9] does.

We compare Obj-GAN with P-AttnGAN w/ Lyt under three settings, with each corresponding to a set of conditional layout input, *i.e.*, the predicted boxes & shapes, the ground-truth boxes & predicted boxes, and the ground-truth boxes & shapes. As presented in Table 1, Obj-GAN consistently outperforms P-AttnGAN w/ Lyt on all three metrics. In Fig. 7, we use the same layout as the conditional input, and compare the visual quality of their generated images. An interesting phenomenon shown in Fig. 7 is that both the foreground objects (e.g., airplane and train) and the background (e.g., airport and trees) textures synthesized by Obj-GAN are much richer and smoother than those using P-AttnGAN w/ Lyt. The effectiveness of the object-driven attention for the foreground objects is easy to understand. The benefits for the background textures using the object-driven attention mechanism is probably due to the fact that it implicitly provides stronger signal that distinguishes the foreground. As such, the image generator may have richer guidance and clearer emphasis when synthesizing textures for a certain region.

Grid attention vs. object-driven attention. We compare Obj-GAN with P-AttnGAN herein, so as to compare the effects of the object-driven and the grid attention mechanisms. In Fig. 8, we show the generated image of each method as well as the corresponding attention maps aligned on the



Figure 7: Qualitative comparison with P-AttnGAN w/ Lyt.



Figure 8: Qualitative comparison with P-AttnGAN. The attention maps of each method are shown beside the generated image.

right side. In a grid attention map, the brightness of a region reflects how much this region attended to the word above the map. As for the object-driven attention map, the word above each attention map is the most attended word by the highlighted object. The highlighted region of an object-driven attention map is the object shape.

As analyzed in § 3.2.1, the reliability of grid attention weights depends on the quality of the previous layer’s image region features. This makes the grid attention unreliable sometimes, especially for complex scenes. For example, the grid attention weights in Fig. 8 are unreliable because they are scattered (e.g., the attention map for “man”) and inaccurate. However, this is not a problem for the object-driven attention mechanism, because its attention weights are directly calculated from embedding vectors of words and class labels and are independent of image features. Moreover, as shown in Fig. 4 and Equ. (6), the impact region of the object-driven attention context vector is bounded by the object shapes, which further enhances its semantics meaningfulness. As a result, the instance-driven attention significantly improves the visual quality of the generated images, as demonstrated in Fig. 8. Moreover, the performance can be further improved if the semantic layout generation is improved. In the extreme case, Obj-GAN based on ground truth layout (Obj-GAN²) has the best visual quality (the rightmost column of Fig. 8) and the best quantitative evaluation (Table 1).

Obj-GAN w/ SN vs. Obj-GAN. We present the comparison between the cases with or without spectral normalization in the discriminators in Table 1 and Fig. 6. We observe that there is no obvious improvement on the visual quality, but slightly worse on the quantitative metrics. We show



Figure 9: Generated images for novel descriptions.

more results and discussions in § ??.

Comparison with previous methods. To compare Obj-GAN with the previous methods, initialized by the Obj-GAN models in the ablation study, we trained Obj-GAN-SOTA with batch size 64 for 10 more epochs. In order to evaluate AttnGAN on FID, we conducted the evaluation on the officially released pre-trained model. Note that the Sg2Im [12] focuses on generating images from scene graphs and conducted the evaluation on a different split of COCO. However, we still included Sg2Im’s results to reflect the broader context of the related topic. As shown in Table 1, Obj-GAN-SOTA outperforms all previous methods significantly. We notice that the increment of batch size does boost the Inception score and R-precision, but does not improve FID. The possible explanation is: with a larger batch size, the DAMSM loss (a ranking loss in essence) in (11) plays a more important role and improves Inception and R-precision, but it does not focus on reducing FID between the generated images and the real ones.

Generalization ability. We further investigate if Obj-GAN just memorizes the scenarios in COCO or it indeed learns the relations between the objects and their surroundings. To this end, we compose several descriptions which reflect novel scenarios that are unlikely to happen in the real-world, e.g., *a decker bus is floating on top of a lake*, or *a cat is catching a frisbee*. We use Obj-GAN to synthesize images for these rare scenes. The results in Fig. 9 further demonstrate the good generalization ability of Obj-GAN.

5. Conclusions

In this paper, we have presented a multi-stage Object-driven Attentive Generative Adversarial Networks (Obj-GANs) for synthesizing images with complex scenes from the text descriptions. With a novel object-driven attention layer at each stage, our generators are able to utilize the fine-grained word/object-level information to gradually refine the synthesized image. We also proposed the Fast R-CNN based object-wise discriminators, each of which is paired with a conditional input of the generator and provides object-wise discrimination signal for that condition. Our Obj-GAN significantly outperforms previous state-of-the-art GAN models on various metrics on the large-scale challenging COCO benchmark. Extensive experiments demonstrate the effectiveness and generalization ability of Obj-GAN on text-to-image generation for complex scenes.

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