

# Cross-Modal Contrastive Learning for Text-to-Image Generation

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## Abstract

The output of text-to-image synthesis systems should be coherent, clear, photo-realistic scenes with high semantic fidelity to their conditioned text descriptions. Our Cross-Modal Contrastive Generative Adversarial Network (XMC-GAN) addresses this challenge by maximizing the mutual information between image and text. It does this via multiple contrastive losses which capture inter-modality and intra-modality correspondences. XMC-GAN uses an attentional self-modulation generator, which enforces strong text-image correspondence, and a contrastive discriminator, which acts as a critic as well as a feature encoder for contrastive learning. The quality of XMC-GAN’s output is a major step up from previous models, as we show on three challenging datasets. On MS-COCO, not only does XMC-GAN improve state-of-the-art FID from 24.70 to 9.33, but—more importantly—people prefer XMC-GAN by 77.3% for image quality and 74.1% for image-text alignment, compared to three other recent models. XMC-GAN also generalizes to the challenging Localized Narratives dataset (which has longer, more detailed descriptions), improving state-of-the-art FID from 48.70 to 14.12. Lastly, we train and evaluate XMC-GAN on the challenging Open Images data, establishing a strong benchmark FID score of 26.91.

## 1. Introduction

Compared to other kinds of inputs (e.g., sketches and object masks), descriptive sentences are an intuitive and flexible way to express visual concepts for generating images. The main challenge for text-to-image synthesis lies in learning from unstructured description and handling the different statistical properties between vision and language inputs.

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<sup>†</sup>Work done as a member of the Google AI Residency program.

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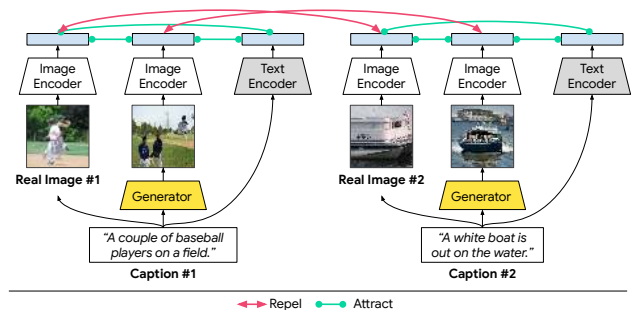


Figure 1: Inter-modal and intra-modal contrastive losses in our proposed XMC-GAN text-to-image synthesis model.

Generative Adversarial Networks (GANs) [12] have shown promising results on text-to-image generation [44, 61, 62], using a conditional GAN formulation [11]. AttnGAN [58] proposes a multi-stage refinement framework to generate fine-grained details by attending to relevant words in the description. These models generate high fidelity images on single domain datasets (e.g., birds [56] and flowers [35]), but struggle on complex scenes with many objects—such as those in MS-COCO [30]. Recent methods [18, 27, 16, 22] propose object-driven, hierarchical approaches that explicitly model object instances within an image. Given the text description, they first infer a semantic layout (e.g., object bounding boxes, segmentation masks, or a combination), and then generate an image from the layout. These hierarchical methods are cumbersome to apply to real-world scenarios; generation becomes a multi-step process (box-to-mask-to-image), and the model requires much more fine-grained object labels to train.

We study contrastive learning in the context of text-to-image synthesis and demonstrate that a simple one-stage GAN *without* object-level annotation can outperform prior object-driven and multi-stage approaches. Besides generating realistic images, we also hope (1) the image should holistically match the description; (2) generated images should match real images when they are conditioned on the

same description; (3) individual image regions should be recognizable and consistent with words in the sentence. To fulfill these desiderata and achieve strong language alignment, we propose to maximize the mutual information between the corresponding pairs through contrastive learning. Our method, the Cross(X)-Modal Contrastive Generative Adversarial Network (XMC-GAN), uses image to sentence, image region to word, and image to image contrastive losses to enforce alignment between generated images and their captions (Fig. 1). Our primary contributions include:

- We propose XMC-GAN, a simple one-stage GAN that employs several contrastive losses. XMC-GAN produces dramatic improvements over previous models, e.g. reducing FID [15] from 24.70 to 9.33 on MS-COCO and from 48.70 to 14.12 on LN-COCO (the MS-COCO portion of Localized Narratives [40]).
- We conduct thorough human evaluations comparing XMC-GAN to three recent models. These show that people prefer XMC-GAN 77.3% of the time for image realism, and 74.1% for image-text alignment.
- We establish a strong benchmark on the challenging LN-OpenImages (Open Images subset of Localized Narratives). To the best of our knowledge, this is the first text-to-image results training and testing on the diverse images and descriptions for Open Images.
- We conduct a thorough analysis of contrastive losses used in XMC-GAN to provide general modeling insights for contrastive learning in conditional GANs.

XMC-GAN consistently produces images that are more coherent and detailed than previous models. In addition to greater realism (with clearer, more delineated objects), they better capture the full image description, including the presence of named objects and background compositions.

## 2. Related Work

**Text-to-image synthesis** Generating images from text descriptions has been quickly improved with deep generative models, including pixelCNN [55, 45], approximate Langevin sampling [34], variational autoencoders (VAEs) [21, 13] and Generative Adversarial Networks (GANs) [12, 44]. GAN-based models in particular have shown better sample quality [61, 64, 58, 66, 59, 26, 52, 42, 24]. GAN-INT-CLS [44] was the first to use conditional GANs for text to image generation. StackGAN [61, 62] improves this with a coarse-to-fine framework that progressively generates images at different resolutions for high-resolution synthesis. AttnGAN [58] introduces cross-modal attention to better capture details. DM-GAN [66] adaptively refines generated images with a memory module that writes and reads text and image features. MirrorGAN [43] enforces text-image consistency via caption generation on the generated images. SD-GAN [59] proposes word-level

conditional batch normalization and dual encoder structure with triplet loss to improve text-image alignment. Compared with the triplet loss, our contrastive loss does not require mining for informative negatives and thus lowers training complexity. CP-GAN [28] proposes an object-aware image encoder and fine-grained discriminator. Its generated images obtain high Inception Score [46]; however, we show it performs poorly when evaluated with the stronger FID [15] metric and in human evaluations (see Sec. 6.1). To create a final high resolution image, these approaches rely on multiple generators and discriminators to generate images at different resolutions. Others have proposed hierarchical models that explicitly generate different objects after inferring semantic layouts [18, 16, 22]. A drawback of these is that they need fine-grained object labels (e.g., object bounding boxes or segmentation maps), so generation is a multi-step process. Compared to these multi-stage and multi-step frameworks, our proposed XMC-GAN only has a single generator and discriminator trained end-to-end, and it generates much higher quality images.

**Contrastive learning and its use in GANs** Contrastive learning is a powerful scheme for self-supervised representation learning [36, 14, 5, 57]. It enforces consistency of image representations under different augmentations by contrasting positive pairs with negative ones. It has been explored under several adversarial training scenarios [25, 65, 9, 41]. Cntr-GAN [65] uses a contrastive loss as regularization on image augmentations for unconditional image generation. ContraGAN [20] explores contrastive learning for class-conditional image generation. DiscoFaceGAN [9] adds contrastive learning to enforce disentanglement for face generation. CUT [39] proposes patch-based contrastive learning for image-to-image translation by using positive pairs from the same image location in input and output images. Unlike prior work, we use intra-modality (image-image) and inter-modality (image-sentence and region-word) contrastive learning in text-to-image synthesis (Fig. 1).

## 3. Preliminaries

### 3.1. Contrastive Representation Learning

Given two random variables  $v_1$  and  $v_2$ , often known as *views* of the data, *contrastive learning* aims to find useful representations of  $v_1$  and  $v_2$  by learning a function that measures the dependence of two views [53], *i.e.*, whether samples are from the joint distribution  $p(v_1)p(v_2|v_1)$  or the product of the marginals  $p(v_1)p(v_2)$ . The resulting function is an estimator of the mutual information  $I(v_1; v_2)$ . As directly maximizing the mutual information is challenging [37, 3, 50], the InfoNCE loss [36] was proposed to maximize a lower bound of the mutual information  $I(v_1; v_2)$ . Specifically, given a query sample  $v_{1,i}$ , minimizing the InfoNCE loss is to score the matching positive sample  $v_{2,i} \sim$

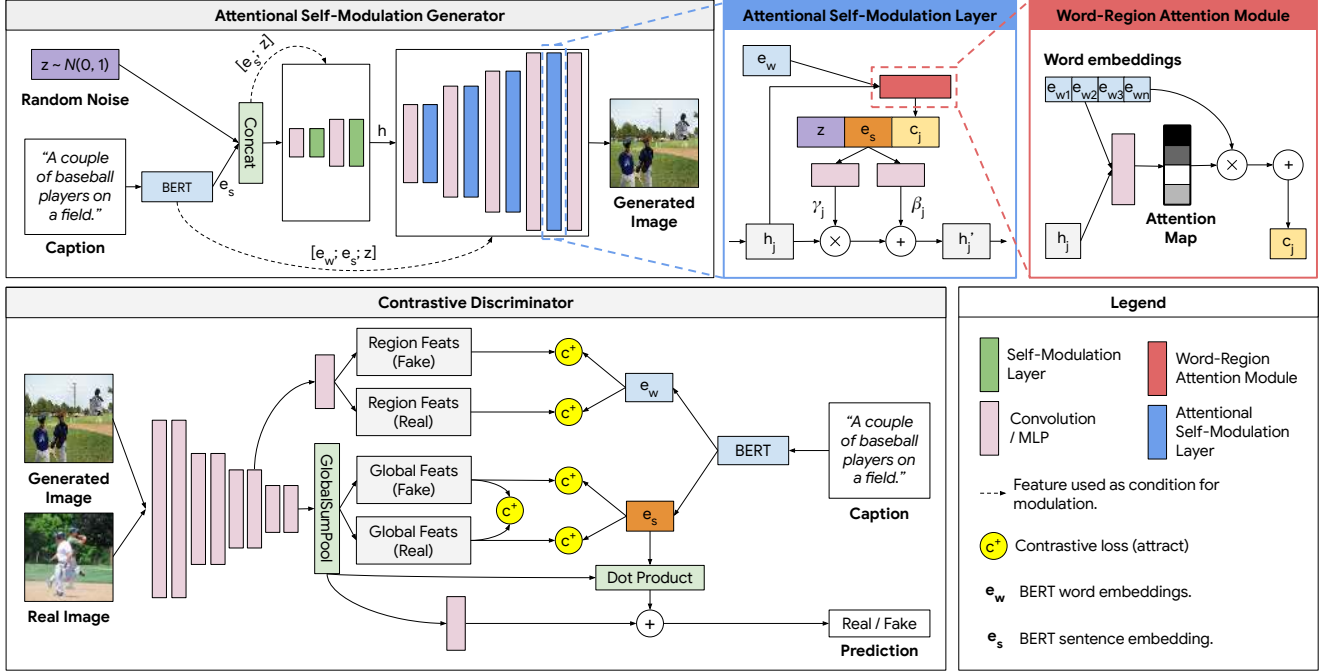


Figure 2: Overview of the proposed XMC-GAN.

$p(v_2|v_{1,i})$  higher than  $M-1$  negative samples  $v_{2,j} \sim p(v_2)$ . The overall objective can be summarized as follows:

$$I(v_1; v_2) \geq \log(M) - \mathcal{L}_{NCE},$$

$$\text{where } \mathcal{L}_{NCE} = -\mathbb{E} \left[ \log \frac{\exp(\mathcal{S}(v_{1,i}, v_{2,i}))}{\sum_{j=1}^M \exp(\mathcal{S}(v_{1,i}, v_{2,j}))} \right].$$

Here,  $\mathcal{S}(\cdot, \cdot)$  is the score function, which typically has two parameterized feature encoders for  $v_1$  and  $v_2$ . The encoders can share parameters if  $v_1$  and  $v_2$  are from the same domain. There are many ways to construct  $v_1$  and  $v_2$ : different augmentations of the same image [14, 5]; spatially adjacent image patches [36]; a video as  $v_1$  and its aligned audio as  $v_2$  for video representation learning [33, 8].

### 3.2. Generative Adversarial Networks (GANs)

GANs [12] are generative models that employ both a generator and a discriminator. The generator  $G$  maps a latent variable  $z \sim p(z)$  (usually sampled from a Gaussian distribution) to a real data distribution  $p_{\text{data}}$ . The discriminator  $D$  is trained to distinguish whether inputs are synthesized or sampled from real data. The generator  $G$  is trained to synthesize images that the discriminator will classify as real.

A large amount of work has focused on designing the adversarial objective to improve training [12, 1, 31, 47, 29, 54]. A notable example is the hinge loss:

$$\begin{aligned} \mathcal{L}_D &= -\mathbb{E}_{x \sim p_{\text{data}}} [\min(0, -1 + D(x))] \\ &\quad - \mathbb{E}_{z \sim p(z)} [\min(0, -1 - D(G(z)))] , \\ \mathcal{L}_G &= -\mathbb{E}_{z \sim p(z)} [D(G(z))]. \end{aligned}$$

The hinge loss has been used in state-of-the-art GANs for image generation [32, 60, 4, 63]. For conditional GANs, the generator and the discriminator are provided with an additional condition  $c$ , yielding  $G(z, c)$  and  $D(x, c)$ . For conditional generation, the generated sample should be both realistic and also match the condition  $c$ .

## 4. Method

We describe the losses and components of XMC-GAN below. See Fig. 2 for an overview.

### 4.1. Contrastive Losses for Text-to-Image Synthesis

Text-to-image synthesis is a conditional generation task. Generated images should both be realistic and well-aligned with a given description. To achieve this, we propose to maximize the mutual information between the corresponding pairs: (1) image and sentence, (2) generated image and real image with the same description, and (3) image regions and words. Directly maximizing mutual information is difficult (see Sec. 3.1), so we maximize the lower bound of the mutual information by optimizing contrastive losses.

**Image-text contrastive loss.** Given an image  $x$  and its corresponding description  $s$ , we define the score function

following previous work in contrastive learning [14, 5, 36]:

$$\mathcal{S}_{\text{sent}}(x, s) = \cos(f_{\text{img}}(x), f_{\text{sent}}(s))/\tau,$$

where  $\cos(u, v) = u^T v / \|u\| \|v\|$  denotes cosine similarity, and  $\tau$  denotes a temperature hyper-parameter.  $f_{\text{img}}$  is an image encoder to extract the overall image feature vector and  $f_{\text{sent}}$  is a sentence encoder to extract the global sentence feature vector. This maps the image and sentence representations into a joint embedding space  $\mathbb{R}^D$ . The contrastive loss between image  $x_i$  and its paired sentence  $s_i$  is computed as:

$$\mathcal{L}_{\text{sent}}(x_i, s_i) = -\log \frac{\exp(\cos(f_{\text{img}}(x_i), f_{\text{sent}}(s_i))/\tau)}{\sum_{j=1}^M \exp(\cos(f_{\text{img}}(x_i), f_{\text{sent}}(s_j))/\tau)}.$$

This form of contrastive loss is also known as the normalized temperature-scaled cross entropy loss (*NT-Xent*) [5].

**Contrastive loss between fake and real images with shared description.** This contrastive loss is also defined with *NT-Xent*. The main difference is that a shared image encoder  $f'_{\text{img}}$  extracts features for both real and fake images. The score function between two images is  $\mathcal{S}_{\text{img}}(x, \tilde{x}) = \cos(f'_{\text{img}}(x), f'_{\text{img}}(\tilde{x}))/\tau$ . The image-image contrastive loss between real image  $x_i$  and generated image  $G(z_i, s_i)$  is:

$$\mathcal{L}_{\text{img}}(x_i, G(z_i, s_i)) = -\log \frac{\exp(\mathcal{S}_{\text{img}}(x_i, G(z_i, s_i)))}{\sum_{j=1}^M \exp(\mathcal{S}_{\text{img}}(x_i, G(z_j, s_j)))}.$$

**Contrastive loss between image regions and words.** Individual image regions should be consistent with corresponding words in an input description. We use attention [58] to learn connections between regions in image  $x$  and words in sentence  $s$ , without requiring fine-grained annotations that align words and regions. We first compute the pairwise cosine similarity matrix between all words in the sentence and all regions in the image; then, we compute the soft attention  $\alpha_{i,j}$  for word  $w_i$  to region  $r_j$  as:

$$\alpha_{i,j} = \frac{\exp(\rho_1 \cos(f_{\text{word}}(w_i), f_{\text{region}}(r_j)))}{\sum_{h=1}^R \exp(\rho_1 \cos(f_{\text{word}}(w_i), f_{\text{region}}(r_h)))},$$

where  $f_{\text{word}}$  and  $f_{\text{region}}$  represent word and region feature encoders respectively,  $R$  is the total number of regions in the image and  $\rho_1$  is a sharpening hyper-parameter to reduce the entropy of the soft attention. The aligned region feature for the  $i^{\text{th}}$  word is defined as  $c_i = \sum_{j=1}^R \alpha_{i,j} f_{\text{region}}(r_j)$ . The score function between all the regions in image  $x$  and all words in sentence  $s$  can then be defined as:

$$\mathcal{S}_{\text{word}}(x, s) = \log \left( \sum_{h=1}^T \exp(\rho_2 \cos(f_{\text{word}}(w_h), c_h)) \right)^{\frac{1}{\rho_2}} / \tau,$$

where  $T$  is the total number of words in the sentence.  $\rho_2$  is a hyper-parameter that determines the weight of the most

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### Algorithm 1 XMC-GAN Training Algorithm.

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**Input:** generator and discriminator parameters  $\theta_G, \theta_D$ , contrastive loss coefficients  $\lambda_1, \lambda_2, \lambda_3$ , Adam hyperparameters  $\beta_1, \beta_2$ , generator and discriminator learning rate  $lr_G, lr_D$ , batch size  $M$ , number of discriminator iterations per generator iteration  $N_D$

```

1: for number of training iterations do
2:   for  $t = 1, \dots, N_D$  do
3:     Sample  $\{z_i\}_{i=1}^M \sim p(z)$ 
4:     Sample  $\{(x_i, s_i)\}_{i=1}^M \sim p_{\text{data}}(x, s)$ 
5:      $\mathcal{L}_{\text{sent}}^r \leftarrow \frac{1}{M} \sum_{i=1}^M \mathcal{L}_{\text{sent}}(x_i, s_i)$ 
6:      $\mathcal{L}_{\text{word}}^r \leftarrow \frac{1}{M} \sum_{i=1}^M \mathcal{L}_{\text{word}}(x_i, s_i)$ 
7:      $\mathcal{L}_{\text{GAN}}^D \leftarrow -\frac{1}{M} \sum_{i=1}^M \min(0, -1 + D(x_i, s_i)) -$ 
        $\frac{1}{M} \sum_{i=1}^M \min(0, -1 - D(G(z_i, s_i), s_i))$ 
8:      $\mathcal{L}_D \leftarrow \mathcal{L}_{\text{GAN}}^D + \lambda_1 \mathcal{L}_{\text{sent}}^r + \lambda_2 \mathcal{L}_{\text{word}}^r$ 
9:      $\theta_D \leftarrow \text{Adam}(\mathcal{L}_D, lr_D, \beta_1, \beta_2)$ 
10:   end for
11:   Sample  $\{z_i\}_{i=1}^M \sim p(z), \{(x_i, s_i)\}_{i=1}^M \sim p_{\text{data}}(x, s)$ 
12:    $\mathcal{L}_{\text{sent}}^f \leftarrow \frac{1}{M} \sum_{i=1}^M \mathcal{L}_{\text{sent}}(G(z_i, s_i), s_i)$ 
13:    $\mathcal{L}_{\text{word}}^f \leftarrow \frac{1}{M} \sum_{i=1}^M \mathcal{L}_{\text{word}}(G(z_i, s_i), s_i)$ 
14:    $\mathcal{L}_{\text{img}} \leftarrow \frac{1}{M} \sum_{i=1}^M \mathcal{L}_{\text{img}}(G(z_i, s_i), x_i)$ 
15:    $\mathcal{L}_{\text{GAN}}^G \leftarrow \frac{1}{M} \sum_{i=1}^M -(D(G(z_i, s_i), s_i))$ 
16:    $\mathcal{L}_G \leftarrow \mathcal{L}_{\text{GAN}}^G + \lambda_1 \mathcal{L}_{\text{sent}}^f + \lambda_2 \mathcal{L}_{\text{word}}^f + \lambda_3 \mathcal{L}_{\text{img}}$ 
17:    $\theta_G \leftarrow \text{Adam}(\mathcal{L}_G, lr_G, \beta_1, \beta_2)$ 
18: end for

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aligned word-region pair, e.g., as  $\rho_2 \rightarrow \infty$ , the score function approximates to  $\max_{h=1}^T \cos(f_{\text{word}}(w_h), c_h)$ . Finally the contrastive loss between the words and regions in image  $x_i$  and its aligned sentence  $s_i$  can be defined as:

$$\mathcal{L}_{\text{word}}(x_i, s_i) = -\log \frac{\exp(\mathcal{S}_{\text{word}}(x_i, s_i))}{\sum_{j=1}^M \exp(\mathcal{S}_{\text{word}}(x_i, s_j))}.$$

## 4.2. Attentional Self-Modulation Generator

We propose a one-stage generator to directly generate the image at the desired resolution. This is much simpler than previous multi-stage generators that create images at multiple, different resolutions. We first sample noise  $z$  from a standard Gaussian distribution. We obtain the global sentence embedding  $e_s$  and the word embeddings  $e_w$  from a pretrained BERT [10] module.  $e_s$  and  $z$  are concatenated to form the global condition, which is passed through several up-sampling blocks (see appendix for details) to generate a  $16 \times 16$  feature map. The global condition is also used as the condition to calculate scale parameter  $\gamma$  and shift parameter  $\beta$  in conditional batch normalization layers. This formulation is also known as self-modulation [6].

The self-modulation layer improves consistency of the hidden feature with the conditional inputs, but it lacks finer details for each sub-region. To generate fine-grained, recog-

nizable regions, we propose the *attentional self-modulation layer*. Specifically, besides random noise  $z$  and global sentence embedding  $e_s$ , we modify the attention mechanism [58] to calculate the word-context vector as the additional modulation parameter for each sub-region. For the  $j^{\text{th}}$  region with feature  $h_j$ , the word-context vector  $c_j$  is:

$$c_j = \sum_{i=1}^T \tilde{\alpha}_{j,i} e_{w_i}, \text{ where } \tilde{\alpha}_{j,i} = \frac{\exp(\rho_0 \cos(e_{w_i}, h_j))}{\sum_{k=1}^T \exp(\rho_0 \cos(e_{w_k}, h_j))},$$

where  $T$  is the total number of words in the sentence and  $\rho_0$  is a sharpening hyper-parameter. Then, the modulated feature  $h'_j$  for the  $j^{\text{th}}$  region can be defined as:

$$h'_j = \gamma_j(\text{concat}(z, e_s, c_j)) \odot \frac{h_j - \mu}{\sigma} + \beta_j(\text{concat}(z, e_s, c_j)),$$

where  $\mu$  and  $\sigma$  are the estimated mean and standard deviation from aggregating both batch and spatial dimensions.  $\gamma_j(\cdot)$  and  $\beta_j(\cdot)$  represent any function approximators; in our work we simply use linear projection layers. Further details of the generator can be found in the appendix.

### 4.3. Contrastive Discriminator

Our proposed discriminator has two roles: (1) to act as a critic to determine whether an input image is real or fake, and (2) to act as an encoder to compute global image and region features for the contrastive loss. The image is passed through several down-sampling blocks until its spatial dimensions are reduced to  $16 \times 16$  (see Fig. 2, bottom left). Then, a  $1 \times 1$  convolution is applied to obtain region features, where the feature dimensions are consistent with the dimensions of the word embedding. The original image feature is fed through two more down-sampling blocks and a global pooling layer. Finally, a projection head computes the logit for the adversarial loss, and a separate projection head computes image features for the image-sentence and image-image contrastive loss. Note that it is important to only use the *real images* and their descriptions to train these discriminator projection heads. The reason is that the generated images are sometimes not recognizable, especially at the start of training. Using such generated image and sentence pairs hurts the training of the image feature encoder projection heads. Therefore, the contrastive losses from *fake images* are only applied to the generator. In addition to the discriminator projection layers, we use a pretrained VGG network [49] as an image encoder for an additional supervisory image-image contrastive loss (see Sec. 6.2). Algorithm 1 summarizes the XMC-GAN training procedure. For simplicity, we set all contrastive loss coefficients ( $\lambda_1, \lambda_2, \lambda_3$  in Algorithm 1) to 1.0 in our experiments.

## 5. Evaluation

### 5.1. Data

We perform a comprehensive evaluation of XMC-GAN on three challenging datasets (summarized in Table 1).

| Dataset             | COCO-14 |     | LN-COCO |     | LN-OpenImages |     |
|---------------------|---------|-----|---------|-----|---------------|-----|
|                     | train   | val | train   | val | train         | val |
| #samples            | 82k     | 40k | 134k    | 8k  | 507k          | 41k |
| caption/image       | 5       |     | 1       |     | 1             |     |
| avg. caption length | 10.5    |     | 42.1    |     | 35.6          |     |

Table 1: Statistics of datasets.

**MS-COCO** [30] is commonly used for text-to-image synthesis. Each image is paired with 5 short captions. We follow most prior work to use the 2014 split (COCO-14) for evaluation.

Localized Narratives [40] contains long form image descriptions for several image collections. We benchmark results on **LN-COCO**, which contains *narratives* for images in the 2017 split of MS-COCO (COCO-17). Narratives are four times longer than MS-COCO captions on average and they are much more descriptive (see Figure 4). Narratives also contain disfluencies since they are spoken and then transcribed. These factors make text-to-image synthesis for LN-COCO much more challenging than MS-COCO.

We also train and evaluate using **LN-OpenImages**, the Open Images [23] split of Localized Narratives. Its images are both diverse and complex (8.4 objects on average). LN-OpenImages is also much larger than MS-COCO and LN-COCO (see Table 1). To the best of our knowledge, we are the first to train and evaluate a text-to-image generation model for Open Images. XMC-GAN is able to generate high quality results, and sets a strong benchmark for this very challenging task.

### 5.2. Evaluation Metrics

Following previous work, we report validation results by generating images for 30,000 random captions<sup>1</sup>. We evaluate comprehensively using several measures.

**Image quality.** We use standard automated metrics for assessing image quality. *Inception Score (IS)* [46] calculates *KL*-divergence between the conditional class distribution and the marginal class distribution given a pre-trained image classifier. *Fréchet Inception Distance (FID)* [15] is the Fréchet distance between two multivariate Gaussians fit to Inception [51] features of generated and real images. While IS and FID have both been shown to correlate with human judgements of generated image quality, IS is likely less informative as it overfits easily and can be manipulated to achieve much higher scores using simple tricks [2, 17]. This is further emphasized by our results (Sec. 6.1) showing that FID correlates better with human judgments of realism.

**Text-Image Alignment.** Following previous work [58, 27], we use *R-precision* to assess whether a generated image can be used to retrieve its conditioning description. However, we notice that previous work computes R-precision

<sup>1</sup>We oversample the images and captions if there are less than 30,000 samples in the validation set.

| Model          | IS $\uparrow$ | FID $\downarrow$   | R-prec (CC) $\uparrow$ | SOA-C $\uparrow$ | SOA-I $\uparrow$ |
|----------------|---------------|--------------------|------------------------|------------------|------------------|
| Real Images    | 34.88         | 6.09               | 69.36                  | 74.97            | 80.84            |
| AttnGAN [58]   | 23.61         | 33.10              | -                      | 25.88            | 39.01            |
| Obj-GAN [27]   | 24.09         | 36.52              | -                      | 27.14            | 41.24            |
| DM-GAN [66]    | 32.32         | 27.34              | -                      | 33.44            | 48.03            |
| OP-GAN [17]    | 27.88         | 24.70              | 49.80                  | 35.85            | 50.47            |
| SD-GAN [59]    | 35.69         | 29.35 <sup>†</sup> | 51.68                  | -                | -                |
| CP-GAN [28]    | <b>52.73</b>  | 55.82 <sup>‡</sup> | 59.05                  | <b>77.02</b>     | <b>84.55</b>     |
| XMC-GAN (ours) | 30.45         | <b>9.33</b>        | <b>71.00</b>           | 50.94            | 71.33            |

Table 2: Comparison of XMC-GAN with previous models on COCO-14. *R-prec (CC)* are R-precision scores computed from a model trained on Conceptual Captions (see Sec. 5.2). <sup>†</sup> indicates scores computed from images shared by the original paper authors, and <sup>‡</sup> indicates scores computed from images generated from the open-sourced models.

using image-text encoders from AttnGAN [58], and many others use these encoders as part of their optimization function during training. This skews results: many generated models report R-precision scores significantly higher than real images. To alleviate this, we use an image-text dual-encoder<sup>2</sup> [38] pretrained on *real images* in the Conceptual Captions dataset [48], which is disjoint from MS-COCO. We find that computing R-precision with independent encoders better correlates with human judgments.

Caption retrieval metrics assess whether the entire image matches the caption. In contrast, *Semantic Object Accuracy (SOA)* [17] evaluates the quality of individual regions and objects within an image. Like previous work, we report SOA-C (*i.e.*, the percentage of images per class in which a desired object is detected) and SOA-I (*i.e.*, the percentage of images in which a desired object is detected). Further details of SOA can be found in [17]. SOA was originally designed for COCO-14, and can take very long to compute as it requires generating multiple samples for each MS-COCO class label. We use the official code to compute the metrics reported in Table 2, but approximate results for LN-COCO and other ablation experiments where we compute results over 30,000 random samples.

**Human evaluation.** Automated metrics are useful while iterating on models during experimentation, but they are no substitute for human eyes. We conduct thorough human evaluations on generated images from 1000 randomly selected captions. For each caption, we request 5 independent human annotators to rank the generated images from best to worst based on (1) realism, and (2) language alignment.

## 6. Experiments

### 6.1. Results

**COCO-14.** Figure 3 shows *human evaluations* comparing XMC-GAN to three recent strong models: CP-GAN [28], SD-GAN [59], and OP-GAN [17]. Given images (anonymized and randomly ordered) generated from the same caption by the four models, annotators are asked

<sup>2</sup>This model will be publicly released to facilitate future evaluations.

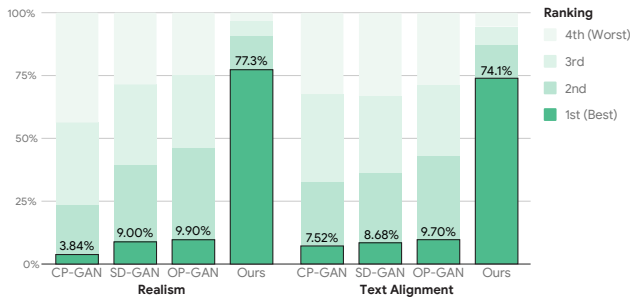


Figure 3: Human evaluation on COCO-14 for image quality and text alignment. Annotators rank (anonymized and order-randomized) generated images from best to worst.

| Model          | IS $\uparrow$ | FID $\downarrow$ | R-prec $\uparrow$ | SOA-C $\uparrow$ | SOA-I $\uparrow$ |
|----------------|---------------|------------------|-------------------|------------------|------------------|
| Real Images    | 34.40         | 8.01             | 61.52             | 66.08            | 67.39            |
| AttnGAN [58]   | 20.80         | 51.80            | 43.88             | -                | -                |
| TRECS [22]     | 21.30         | 48.70            | 37.88             | -                | -                |
| XMC-GAN (ours) | <b>28.37</b>  | <b>14.12</b>     | <b>66.92</b>      | 36.76            | 48.14            |

Table 3: Comparison of XMC-GAN on LN-COCO. SOA metrics together with others are computed from 30,000 random examples.

to rank them from best to worst. Realism and text alignment judgments are collected independently. XMC-GAN is the clear winner on both: its output is ranked best in 77.3% of realism comparisons, and 74.1% of text alignment ones. OP-GAN is a distant second, at 9.90% and 9.70%, respectively. XMC-GAN achieves this while being a simpler, one-stage model, whereas OP-GAN is multi-stage and needs object bounding boxes. Visual inspection of selected images (Fig. 4) convincingly shows the large quality improvement. XMC-GAN’s images are much higher fidelity compared to others, and depict clearer objects and more coherent scenes. This also holds for more random samples (see appendix).

Table 2 provides comprehensive COCO-14 results for *automated* metrics. XMC-GAN dramatically improves FID from 24.70 to 9.33, a 62.2% relative improvement over the next best model, OP-GAN [17]. XMC-GAN also outperforms others (71% vs. 59%) for R-precision computed with our *independently trained* encoders, indicating a large im-

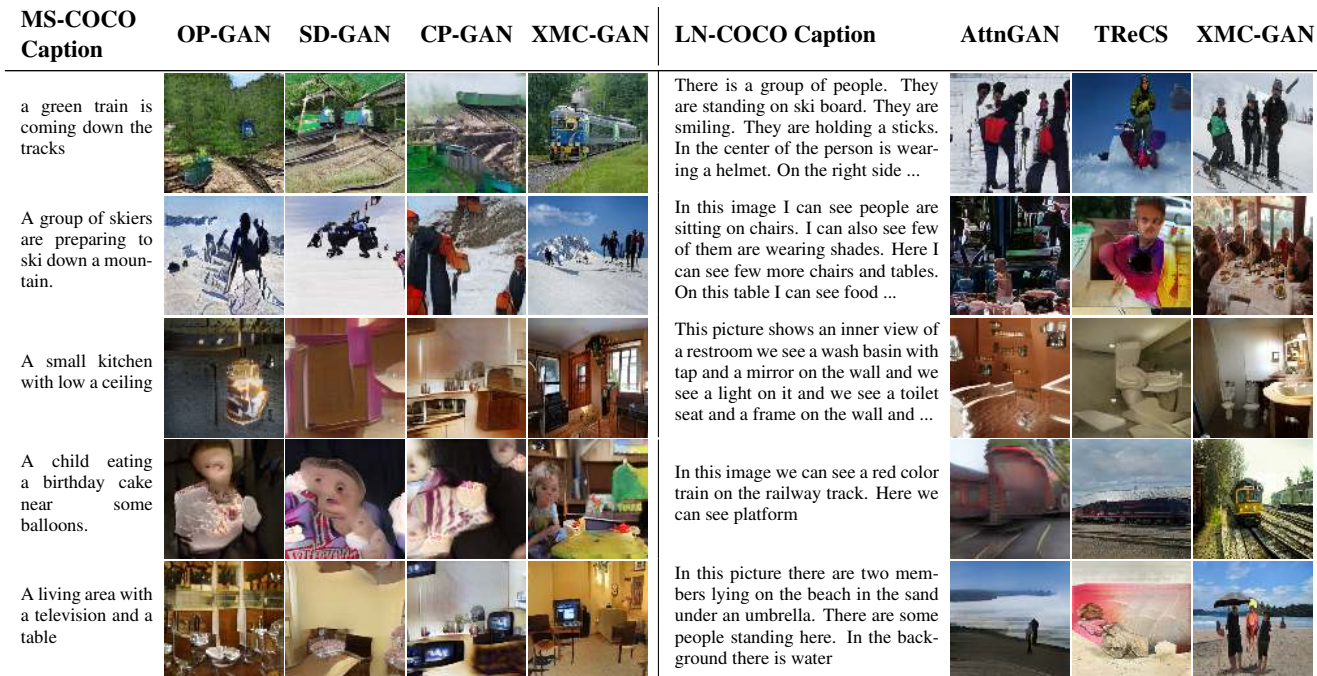


Figure 4: Generated images for selected examples from COCO-14 and LN-COCO. XMC-GAN generated images are generally of much higher quality and depict clearer scenes. More random samples are available in the appendix.

provement in fidelity of generated images to the captions they are conditioned on—and consistent with human judgments. Although CP-GAN achieves higher IS and SOA scores, both our human evaluations and visual inspection of randomly selected images indicates XMC-GAN’s image quality is much higher than CP-GAN’s. This may be due to the issue that IS and SOA do not penalize intra-class mode dropping (low diversity within a class)—a model that generates one “perfect” sample for each class can achieve good scores on IS and SOA. Our findings are consistent with other works [27, 2], which suggest that FID may be a more reliable metric for measuring text-to-image synthesis quality.

**LN-COCO.** Localized Narratives [40] contains much longer descriptions, which increases the difficulty of text-to-image synthesis (see Sec. 5.1). Table 3 shows that XMC-GAN provides massive improvements over prior work. Compared to TReCS [22], XMC-GAN improves IS and FID, by 7.07 and 34.58 (absolute), respectively. It also improves R-precision by 23.04% absolute over AttnGAN [58], indicating much better text alignment. This is supported by qualitative comparison of randomly selected outputs: XMC-GAN’s images are decisively clearer and more coherent (see Fig. 4). We stress that TReCS exploits LN-COCO’s mouse trace annotations—incorporating this training signal in XMC-GAN in future should further boost performance.

| S                | W | I       | IS ↑         | FID ↓        | R-prec ↑     | SOA-C ↑      | SOA-I ↑      |
|------------------|---|---------|--------------|--------------|--------------|--------------|--------------|
| Real Images [17] |   |         |              |              |              |              |              |
|                  |   |         | 34.88        | 6.09         | 69.36        | 76.17        | 80.12        |
| ✓                |   |         | 15.89        | 39.28        | 21.41        | 8.99         | 25.72        |
|                  | ✓ |         | 23.50        | 19.25        | 53.57        | 24.57        | 45.41        |
|                  |   | D       | 20.72        | 24.38        | 44.42        | 20.50        | 39.12        |
|                  |   | D       | 18.90        | 29.71        | 31.16        | 12.73        | 30.89        |
|                  |   | VGG     | 21.54        | 39.58        | 35.89        | 17.41        | 35.08        |
|                  |   | D + VGG | 23.61        | 21.14        | 47.04        | 23.87        | 44.41        |
| ✓                | ✓ |         | 26.02        | 14.25        | 64.94        | 30.49        | 51.60        |
| ✓                | ✓ | D       | 28.06        | 12.96        | 65.36        | 34.21        | 54.23        |
| ✓                | ✓ | VGG     | 30.55        | <b>11.12</b> | <b>70.98</b> | 39.36        | 59.10        |
| ✓                | ✓ | D + VGG | <b>30.66</b> | 11.93        | 69.86        | <b>39.85</b> | <b>59.78</b> |

Table 4: Ablation results with different contrastive losses on COCO-14. **S** indicates the sentence-image loss. **W** indicates the region-word loss. **I** indicates the image-image loss, where D represents using the discriminator to extract image features, and VGG represents using a pre-trained VGG network to extract image features.

**LN-OpenImages.** We train XMC-GAN on Open Images dataset, which is much more challenging than MS-COCO due to greater diversity in images and descriptions. XMC-GAN achieves an IS of 24.90, FID of 26.91, and R-precision of 57.55, and manages to generate high quality images (see appendix). To the best of our knowledge, XMC-GAN is the first text-to-image model trained and evaluated on Open Images. Its strong automated scores establish strong benchmark results on this challenging dataset.

## 6.2. Ablations

We thoroughly evaluate the different components of XMC-GAN and analyze their impact. Table 4 summarizes

| Modulation                  | IS $\uparrow$ | FID $\downarrow$ | R-prec $\uparrow$ | SOA-C $\uparrow$ | SOA-I $\uparrow$ |
|-----------------------------|---------------|------------------|-------------------|------------------|------------------|
| Self-modulation             | 28.98         | 13.59            | 64.65             | 35.18            | 55.54            |
| Attentional self-modulation | <b>30.66</b>  | <b>11.93</b>     | <b>69.86</b>      | <b>39.85</b>     | <b>59.78</b>     |

Table 5: Comparison of different modulation layers.

| VGG Loss                   | IS $\uparrow$ | FID $\downarrow$ | R-prec $\uparrow$ | SOA-C $\uparrow$ | SOA-I $\uparrow$ |
|----------------------------|---------------|------------------|-------------------|------------------|------------------|
| $l_2$ loss                 | 12.46         | 52.86            | 22.62             | 8.27             | 25.48            |
| Contrastive (InfoNCE) loss | <b>21.54</b>  | <b>39.58</b>     | <b>35.89</b>      | <b>17.41</b>     | <b>35.08</b>     |

Table 6: Comparison of different VGG losses.

our ablations<sup>3</sup> on the COCO-14 validation set. To study the effects of each contrastive loss component used in XMC-GAN, we experiment with four losses: (1) image-sentence, (2) region-word, (3) image-image using discriminator features, and (4) image-image using VGG features. For (3), we use the discriminator encoder projection (indicated by D in Table 4) to extract image features. For (4), we extract image features from a VGG-19 network [49] pretrained on ImageNet.

**Individual contrastive losses.** Table 4 shows that using any of the contrastive losses improves all metrics compared to the baseline. During experimentation, we also found that including any contrastive loss greatly improves training stability. The largest improvements come from the *inter-modal* image-sentence and region-word contrastive losses, which improve FID from 39.28 to 19.25 and 24.38, respectively. This is much larger compared to the image-image *intra-modal* contrastive losses, *e.g.*, including the loss from the discriminator feature encoder (D) only improves FID to 29.71. These ablations highlight the effectiveness of inter-modal contrastive losses: sentence and word contrastive losses each greatly improve the text-alignment metrics, as well as improving image quality.

**Combined contrastive losses.** Combining contrastive losses provides further gains. For example, using both image-sentence and region-word losses achieves better performance (FID 14.25) than alone (FID 19.25 and 24.38, respectively). This demonstrates that local and global conditions are complementary. Moreover, using both inter-modal losses (sentence and words) outperforms the intra-modal losses (D + VGG): FID scores are 14.25 and 21.14, respectively. These results further emphasize the effectiveness of cross-modal contrastive learning. Nevertheless, the *inter-modal* and *intra-modal* contrastive losses also complement each other: the best FID score comes from combining image-sentence, region-word, and image-image (VGG) losses. Performance on IS and text alignment further improves when using the image-image (D + VGG) loss. To obtain our final results (Table 2), we train a model (with base channels dimension 96) using all 4 contrastive losses.

<sup>3</sup>All ablation results (Fig. 5, Tables 4, 5, and 6) are reported using metrics re-implemented in TensorFlow. SOA is approximated using 30,000 random samples. Ablation models use a reduced base channels dimension of 64. Implementation details are provided in the appendix.

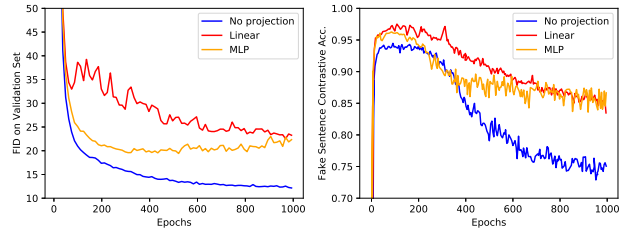


Figure 5: Comparison between different contrastive heads.

**Deeper contrastive heads.** In unsupervised representation learning [5, 7], adding non-linear layers generally improves performance. To study this, we increase the depth of the projection head in the discriminator. Training curves for FID and contrastive accuracy [5] on fake images are in Fig. 5, across 1000 epochs. We find that using no additional projection layers gives the best FID (12.61, compared to 19.42 of the 2-layer MLP). Moreover, we also find that the contrastive accuracy increases on fake images (from 76.56% to 88.55%) when more layers are added to the projection head. We posit that the discriminator overfits to the contrastive learning task in this configuration, resulting in poorer performance on the adversarial task as a critic and hence worse as a supervisory signal for the generator.

**Attentional Self-Modulation.** We compare two generator setups: (1) self-modulation layers [6] in all residual blocks, and (2) attentional self-modulation layers (see Sec. 4.2) for blocks with input resolution larger than  $16 \times 16$ . Table 5 shows that the proposed attentional self-modulation layer outperforms self-modulation on all metrics.

**Loss types.** A frequently used loss function in generative models is the  $l_2$  loss over VGG [49] outputs between fake images and corresponding real images. This is also commonly known as the perceptual loss [19]. Table 6 shows that contrastive losses outperform such perceptual losses. This demonstrates that repelling mismatched samples is more effective than simply pulling together aligned samples. Given this superior performance, replacing perceptual losses with contrastive losses may help other generative tasks.

## 7. Conclusion

In this work, we present a cross-modal contrastive learning framework to train GAN models for text-to-image synthesis. We investigate several cross-modal contrastive losses that enforce correspondence between image and text. With both human and automated evaluations on multiple datasets, XMC-GAN establishes a marked improvement over previous models: it generates higher quality images that better match their input descriptions, including for long, detailed narratives. It does so while being a simpler, end-to-end model. We believe that these advances are strong leaps towards creative applications for image generation from natural language descriptions.



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