ON SELF-SUPERVISED IMAGE REPRESENTATIONS FOR GAN EVALUATION

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ABSTRACT

The embeddings from CNNs pretrained on Imagenet classification are de-facto standard image representations for assessing GANs via FID, Precision and Recall measures. Despite broad previous criticism of their usage for non-Imagenet domains, these embeddings are still the top choice in most of the GAN literature.

In this paper, we advocate the usage of the state-of-the-art self-supervised representations to evaluate GANs on the established non-Imagenet benchmarks. These representations, typically obtained via contrastive learning, are shown to provide better transfer to new tasks and domains, therefore, can serve as more universal embeddings of natural images. With extensive comparison of the recent GANs on the common datasets, we show that self-supervised representations produce a more reasonable ranking of models in terms of FID/Precision/Recall, while the ranking with classification-pretrained embeddings often can be misleading.

1 INTRODUCTION

Generative adversarial networks (GANs) are an extremely active research direction in the machine learning. The intensive development of the field requires established quantitative measures to assess constantly appearing models. While a large number of evaluation protocols were proposed (Borji, 2019; Xu et al., 2018; Zhou et al., 2019; Naeem et al., 2020), there is still no consensus regarding the best evaluation measure. Across the existing measures, the Fréchet Inception Distance (FID) (Heusel et al., 2017) and Precision/Recall (Kynkäänniemi et al., 2019) are the most widely adopted due to their simplicity and decent consistency with human judgments. FID and Precision/Recall quantify the discrepancy between distributions of real and generated images. Since these distributions are complicated to describe in the original RGB space, the images are represented by embeddings, typically extracted with CNNs pretrained on the Imagenet classification task (Deng et al., 2009). While FID computed with these embeddings was shown to correlate with human evaluation (Heusel et al., 2017), these observations were mostly obtained on the datasets, semantically close to Imagenet. Meanwhile, on non-Imagenet datasets, these embeddings can provide inadequate evaluation, as widely reported in the literature (Rosca et al., 2017; Barratt & Sharma, 2018; Zhou et al., 2019).

In this work, we propose to employ the state-of-the-art self-supervised models (Chen et al., 2020; He et al., 2020; Caron et al., 2020) to extract image embeddings for GAN evaluation. These models were shown to produce features that transfer better to new tasks, hence, they become a promising candidate to provide a more universal representation. Intuitively, classification-pretrained embeddings by design can suppress the information, irrelevant for the Imagenet class labels, which, however, can be crucial for other domains, like human faces. On contrary, self-supervised models, mostly trained via contrastive learning, do not have such a bias, since their main goal is typically to learn invariances to common image augmentations.

To justify the usage of self-supervised embeddings, we perform a thorough comparison of the recent GAN models trained on the five most common benchmark datasets. We demonstrate that classification-pretrained embeddings can lead to incorrect ranking in terms of FID, Precision, and Recall, which are the most popular metrics. On the other hand, self-supervised representations produce more reasonable ranking, advocating their advantage over "classification-oriented" counterparts. Since all the checkpoints needed to compute self-supervised embeddings are publicly available, they can serve as a handy instrument for GAN comparison, consistent between different papers.

Overall, the contributions of this paper are summarized as follows:

1. To the best of our knowledge, our work is the first to employ self-supervised image representations obtained via contrastive learning to evaluate GANs trained on natural images.
2. By extensive experiments on the common non-Imagenet benchmarks, we demonstrate that the usage of self-supervised representations provides more accurate GAN comparison.
3. We have evaluated a large number of publicly available GANs in terms of "self-supervised" FID, Precision and Recall, providing these values for further research as a reference.

2 RELATED WORK

GAN evaluation measures. Over the last years, a variety of quantitative GAN evaluation methods have been developed by the community, and the development process has yet to converge, since all the measures possess specific weaknesses (Borji, 2019; Xu et al., 2018). The Inception Score (Salimans et al., 2016) was the first widely adopted measure, but was shown to be hardly applicable for non-Imagenet domains (Barratt & Sharma, 2018). The Fréchet Inception Distance (FID) (Heusel et al., 2017) quantifies dissimilarity of real and generated distributions, computing the Wasserstein distance between their gaussian approximations, and is currently the most popular scalar measure of GAN's quality. Several recent measures were proposed (Sajjadi et al., 2018; Kynkäänniemi et al., 2019; Naeem et al., 2020) that separately evaluate fidelity and diversity of GAN-produced images. All of them mostly use the embeddings produced by the Imagenet classification CNN. A recent work (Zhou et al., 2019) has introduced a human-in-the-loop measure, which is more reliable compared to automated ones, but cannot be used e.g. for monitoring the training process. We focus on three the most widely used measures: FID, Precision, and Recall, which are discussed briefly below.

Fréchet Inception Distance quantifies the discrepancy between the distributions of real and generated images, denoted by p_D and p_G. Both p_D and p_G are defined on the high-dimensional image space forming nontrivial manifolds, which are challenging to approximate by simple functions. To be practical, FID operates in the lower-dimensional space of image embeddings. Formally, the embeddings are defined by a map $f : \mathbb{R}^N \to \mathbb{R}^d$, where N and d correspond to the dimensionalities of the images and embeddings spaces respectively. By design, FID measures the dissimilarity between the induced distributions fp_D, fp_G as follows. First, fp_D and fp_G are approximated by Gaussian distributions. Then the Wasserstein distance between these distributions is evaluated. As was shown in (Dowson & Landau, 1982), for distributions defined by the means μ_D, μ_G and the covariance matrices Σ_D, Σ_G, this quantity equals to $\|\mu_D - \mu_G\|_2^2 + \text{tr}(\Sigma_D + \Sigma_G - 2(\Sigma_D\Sigma_G)^{\frac{1}{2}})$. Lower FID values correspond to higher similarity between p_G and p_D; hence, can be used to evaluate the performance of generative models. As a common practice in the FID computation, one typically uses the activations from the InceptionV3 (Szegedy et al., 2016) pretrained on Imagenet classification.

Precision and Recall. When assessing generative models, it is important to quantify both the visual quality of generated images and the model diversity, e.g., to diagnose mode collapsing. However, the scalar FID values were shown (Sajjadi et al., 2018; Kynkäänniemi et al., 2019) to sacrifice diversity in favor of visual quality, therefore FID cannot serve as the only sufficient metric. To this end, (Sajjadi et al., 2018) introduced Precision and Recall, which aim to measure the image realism and the model diversity respectively. A recent follow-up (Kynkäänniemi et al., 2019) elaborates on these metrics and proposes a reasonable procedure to quantify both precision and recall based only on the image embeddings. In a nutshell, (Kynkäänniemi et al., 2019) assumes that the visual quality of a particular sample is high if its embedding is neighboring for the embeddings of the real images. On the other hand, a given real image is considered covered by the model, if its embedding belongs to the neighborhood of embeddings of the generated images.

Self-supervised representations. Self-supervised learning is currently attracting much research attention, especially to the contrastive learning methods (Chen et al., 2020; He et al., 2020; Caron et al., 2020). The common idea behind contrastive methods is to construct representations that are close for positive image pairs and distant for negative ones, where positive pairs are produced automatically via augmentations. The recent self-supervised methods were shown to provide more transferrable (He et al., 2020; Caron et al., 2020) and robust (Hendrycks et al., 2019) features, which implies their usage as more universal representations. In this paper, we show them being a better alternative compared to established classifier-produced embeddings in the context of GAN assessment.

3 GAN EVALUATION

Here we systematically compare the publicly available GANs to highlight the cases of misleading comparison with classification-pretrained embeddings. Our goal is to demonstrate that in these cases self-supervised embeddings are a better alternative, while in other cases the rankings with both types of embeddings are mostly consistent. We examine GANs trained on five popular benchmarks:

- **CelebaHQ 1024x1024** (Karras et al., 2017) with the following GAN models: StyleGAN without truncation (Karras et al., 2019a), MSG (Karnewar & Wang, 2020) with truncation 0.6 and without it, PGGAN (Karras et al., 2017). To compute the metrics, we use 30k real and synthetic images;
- **FFHQ 1024x1024** (Karras et al., 2019a) with the following GAN models: StyleGAN (Karras et al., 2019a), StyleGAN2 (Karras et al., 2019b), MSG (Karnewar & Wang, 2020) with truncation 0.6 and without it. To compute the metrics, we use 30k real and synthetic images;
- **LSUN Bedroom 256x256** (Yu et al., 2015) with the following GAN models: StyleGAN (Karras et al., 2019a), PGGAN (Karras et al., 2017), COCO-GAN (Lin et al., 2019), RPGAN (Voynov & Babenko, 2019), RPGAN with high diversity (RPGAN div.). RPGAN generates 128x128 images, so we upscale them to 256x256. To compute the metrics, we use 30k real and synthetic images;
- **LSUN Church 256x256** (Yu et al., 2015) with the models: StyleGAN2 (Karras et al., 2019b) with truncation 0.5 and without it, MSG (Karnewar & Wang, 2020) with truncation 0.6 and without it, PGGAN (Karras et al., 2017), SNGAN (Miyato et al., 2018). SNGAN generates 128x128 images, so we upscale them to 256x256. To compute the metrics, we use 100k real and synthetic images;
- **Imagenet 128x128** (Deng et al., 2009) with the following GAN models: BigGAN (Brock et al., 2019), BigGAN-deep (Brock et al., 2019), S3GAN (Lucic et al., 2019), Your Local GAN (YLG) (Daras et al., 2020). To compute the metrics, we use 50k real and synthetic images (50 per class);. We include this dataset to demonstrate that for Imagenet, the proposed self-supervised representations provide consistent ranking with commonly used InceptionV3 embeddings.

To compute image embeddings, we use the following publicly available models:

- **InceptionV3** (Szegedy et al., 2016) pretrained on the ILSVRC-2012 task (Deng et al., 2009);
- **Resnet50** (He et al., 2016) pretrained on the ILSVRC-2012 task. We include this model since self-supervised models employ Resnet50, therefore, it is important to demonstrate that better GAN ranking comes from the training objective rather than the deeper architecture;
- **Imagenet21k** (Kolesnikov et al., 2019) pretrained on the multi-label classification task on approximately 14M images from the full Imagenet. Kolesnikov et al. (2019) have shown that supervised pretraining on huge datasets provides more transferrable features, therefore, **Imagenet21k** can also potentially provide more universal representations. The model architecture is Resnet50;
- **SwAV** (Caron et al., 2020) is the state-of-the-art self-supervised image representation model trained on ILSVRC-2012. The idea of SwAV is to simultaneously cluster the images, while enforcing consistency between cluster assignments produced for different augmentations of the same image. The model architecture is Resnet50;
- **DeepClusterV2** (Caron et al., 2020) is another self-supervised model obtained by alternating between pseudo-labels generation via k-means clustering and training the network with a classification loss supervised by these pseudo-labels. The model architecture is Resnet50;

Two self-supervised models listed above outperform supervised pretraining on a number of transfer tasks (Caron et al., 2020), which implies that their embeddings capture more information relevant for these tasks, compared to supervised models pretrained on Imagenet. Below, for a large number of publicly available GANs, we present the values of FID, Precision, and Recall metrics computed with different embeddings. For the cases, where the GANs ranking is inconsistent, we aim to show that the ranking obtained with the self-supervised representations is more reasonable.

3.1 FRÉCHET INCEPTION DISTANCE

The FID values for the non-Imagenet datasets computed with different embeddings are shown in Table 1. The cases of inconsistent ranking with supervised InceptionV3 and self-supervised SwAV embeddings are highlighted in color. The key observations are listed below:

Table 1: FID values computed with different embeddings. The '*' symbol indicates models with truncation. The inconsistencies between InceptionV3 and SwAV rankings are highlighted in color.

	CELEBAHQ				FFHQ			
InceptionV3	MSG 7.041	PGGAN 7.747	StyleGAN 12.761	MSG* 18.845	StyleGAN2 3.355	MSG 6.560	StyleGAN 6.896	MSG* 22.552
Resnet50	MSG 7.427	PGGAN 9.395	StyleGAN 13.650	MSG* 19.048	StyleGAN2 3.813	MSG 7.252	StyleGAN 8.230	MSG* 25.076
Imagenet21k	MSG 295.3	PGGAN 451.6	StyleGAN 635.5	MSG* 874.4	StyleGAN2 177.7	MSG 334.7	StyleGAN 389.1	MSG* 1092
SwAV	MSG 1.206	StyleGAN 1.473	MSG* 1.832	PGGAN 1.898	StyleGAN2 0.634	MSG 1.275	StyleGAN 1.482	MSG* 2.461
DeepClusterV2	MSG 1.847	StyleGAN 2.680	PGGAN 2.865	MSG* 2.935	StyleGAN2 0.978	MSG 1.890	StyleGAN 2.076	MSG* 3.926

	LSUN-BEDROOM				
InceptionV3	PGGAN 8.658	StyleGAN 9.655	COCO-GAN 18.612	RPGAN 37.924188	RPGAN div. 40.165
Resnet50	PGGAN 17.689	StyleGAN 20.042	COCO-GAN 34.045	RPGAN 44.850	RPGAN div. 51.850
Imagenet21k	StyleGAN 633.3	PGGAN 940.6	COCO-GAN 1270	RPGAN div. 1589	RPGAN 1593
SwAV	StyleGAN 1.776	PGGAN 4.160	RPGAN 5.608	COCO-GAN 6.289	RPGAN div. 6.460
DeepClusterV2	StyleGAN 2.958	PGGAN 5.855	RPGAN 8.757	COCO-GAN 9.151	RPGAN div. 10.13

	LSUN-CHURCH					
InceptionV3	StyleGAN2 3.652	MSG 5.009	PGGAN 6.296	MSG* 13.854	StyleGAN2* 24.966	SNGAN 32.661
Resnet50	StyleGAN2 6.650	MSG 9.673	PGGAN 10.850	MSG* 22.670	StyleGAN2* 55.571	SNGAN 56.114
Imagenet21k	StyleGAN2 558.1	MSG 856.8	PGGAN 946.0	MSG* 1305.3	SNGAN 1715	StyleGAN2* 2165
SwAV	StyleGAN2 1.898	PGGAN 3.233	MSG 3.578	MSG* 4.062	StyleGAN2* 5.194	SNGAN 6.043
DeepClusterV2	StyleGAN2 2.599	PGGAN 4.149	MSG 4.586	MSG* 5.395	SNGAN 7.830	StyleGAN2* 8.612

(a) On the CelebaHQ dataset, SwAV ranks StyleGAN higher, while InceptionV3/Resnet50 prefer PGGAN. Figure 1 shows random samples from both StyleGAN and PGGAN and clearly demonstrates the superiority of StyleGAN. To investigate the reasons why SwAV produces more adequate ranking compared to Inception/Resnet50, we perform two additional experiments. *(I)* First, we verify that SwAV embeddings capture more information, relevant for face images. The Celeba dataset (Liu et al., 2018) provides labels of 40 attributes for each image, describing various person properties (gender, age, hairstyle, etc.). For each attribute, we train 4-layer feedforward neural network with 2048 neurons on each layer with cross-entropy loss, which learns to predict the attribute from the SwAV/Inception embedding. For all attributes, the predictions from SwAV embeddings appear to be more accurate compared to InceptionV3 (several examples are given in Table 2). It confirms the intuition that InceptionV3 representations partially suppress the information about small facial details, which, however, is critical to identify more realistic images. *(II)* As a qualitative experiment,

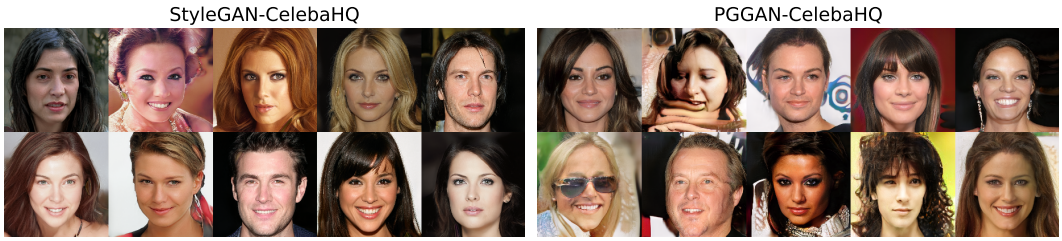

Figure 1: Samples generated by StyleGAN and PGGAN trained on CelebaHQ. The quality of images generated by StyleGAN is substantially higher.

Table 2: Prediction accuracy of CelebaHQ attributes from InceptionV3 and SwAV embeddings.

Model	Mouth Slightly Open	No Beard	High Cheekbones	Smiling
InceptionV3	0.802	0.906	0.811	0.837
SwAV	0.868	0.938	0.851	0.893

we compare SwAV and supervised Resnet50 embeddings visually via a recent technique described in Rombach et al. (2020). In a nutshell, this technique reveals the invariances learnt by the particular representation model: for a given image, it visualizes several images, having approximately the same embedding. By inspecting these images, one can analyze what factors of variations are not captured in the embedding (see the details in Section A.1). Two illustrative examples of such visualization for SwAV and Resnet50 are shown in Figure 2, demonstrating that Resnet50 embeddings are more invariant to sensitive information, like gender or race, compared to SwAV. Such ignorance of sensitive information makes supervised embeddings less appealing to use as universal representations.

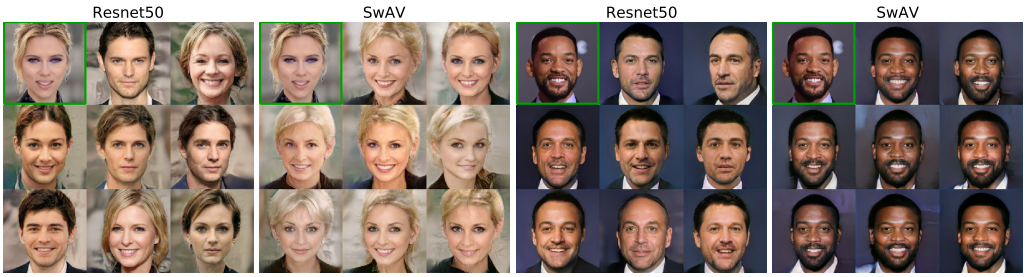

Figure 2: The reference image is top-left denoted by a green frame, while 8 others constitute a diverse sample of images that have approximately the same embeddings as the reference one.

(b) On the Bedroom dataset, there are two inconsistencies in InceptionV3 and SwAV ranking. The first is that SwAV ranks StyleGAN higher than PGGAN and the second is that SwAV ranks RPGAN higher than COCO-GAN. Figure 3 shows the samples from StyleGAN, PGGAN, RPGAN, and COCO-GAN and demonstrates that the ranking according to SwAV embeddings is more adequate. Namely, the quality of StyleGAN-generated images is substantially higher. Also, it is difficult to identify a favorite among RPGAN and COCO-GAN visually, while InceptionV3 embeddings claim strong superiority of the COCO-GAN model. On the other hand, self-supervised embeddings consider these models as comparable, which is better aligned with human perception.

(c) There is also a case of the inconsistent ranking of Church models, namely MSG and PGGAN. But since the difference of the FID values for MSG and PGGAN is small for both InceptionV3 and SwAV, we do not consider it as a strong disagreement.

Figure 3: Samples generated by StyleGAN, PGGAN, RPGAN and COCO-GAN trained on Bedroom dataset. The quality of images generated by StyleGAN is substantially higher, while the quality of the images generated by RPGAN and COCO-GAN is approximately the same.

Table 3: Precision values for different embedding models. The '*' symbol indicates models with truncation. Inconsistencies between InceptionV3 and SwAV models are highlighted in color. To calculate Precision, we use the neighborhood size $k = 5$.

	CELEBAHQ				FFHQ			
InceptionV3	MSG* 0.894	StyleGAN 0.882	MSG 0.7963	PGGAN 0.778	MSG* 0.843	StyleGAN2 0.778	StyleGAN 0.778	MSG 0.776
Resnet50	StyleGAN 0.921	MSG* 0.916	MSG 0.839	PGGAN 0.839	MSG* 0.865	StyleGAN2 0.821	StyleGAN 0.807	MSG 0.789
Imagenet21k	StyleGAN 0.923	MSG* 0.912	PGGAN 0.904	MSG 0.868	StyleGAN2 0.883	MSG* 0.875	StyleGAN 0.871	MSG 0.851
SwAV	MSG* 0.935	StyleGAN 0.928	MSG 0.879	PGGAN 0.851	MSG* 0.911	StyleGAN 0.905	StyleGAN2 0.889	MSG 0.870
DeepClusterV2	MSG* 0.945	StyleGAN 0.937	PGGAN 0.890	MSG 0.887	MSG* 0.920	StyleGAN 0.908	StyleGAN2 0.882	MSG 0.873

	LSUN-BEDROOM				
InceptionV3	StyleGAN 0.799	PGGAN 0.541	COCO-GAN 0.443	RPGAN div. 0.092	RPGAN 0.086
Resnet50	StyleGAN 0.849	PGGAN 0.646	COCO-GAN 0.596	RPGAN div. 0.545	RPGAN 0.515
Imagenet21k	StyleGAN 0.723	COCO-GAN 0.622	PGGAN 0.434	RPGAN div. 0.171	RPGAN 0.114
SwAV	StyleGAN 0.849	PGGAN 0.732	COCO-GAN 0.725	RPGAN div. 0.540	RPGAN 0.440
DeepClusterV2	StyleGAN 0.817	PGGAN 0.722	COCO-GAN 0.706	RPGAN div. 0.540	RPGAN 0.423

	LSUN-CHURCH					
InceptionV3	StyleGAN2* 0.909	MSG* 0.837	MSG 0.698	PGGAN 0.692	StyleGAN2 0.689	SNGAN 0.193
Resnet50	StyleGAN2* 0.910	MSG* 0.828	MSG 0.679	StyleGAN2 0.672	PGGAN 0.639	SNGAN 0.403
Imagenet21k	StyleGAN2* 0.567	StyleGAN2 0.492	MSG* 0.458	MSG 0.448	PGGAN 0.399	SNGAN 0.183
SwAV	StyleGAN2* 0.929	MSG* 0.647	StyleGAN2 0.619	PGGAN 0.533	MSG 0.491	SNGAN 0.465
DeepClusterV2	StyleGAN2* 0.936	MSG* 0.779	StyleGAN2 0.630	MSG 0.593	PGGAN 0.589	SNGAN 0.438

(d) The rankings with the supervised InceptionV3/Resnet50 embeddings are consistent with each other, while being different from the rankings with the self-supervised ones. It indicates that the model architecture does not affect GAN ranking, and it is the training objective that matters.

(e) Imagenet21k corrects some cases of misleading ranking with InceptionV3, but not all of them. Namely, it correctly ranks StyleGAN and PGGAN on Bedroom, while being wrong on CelebaHQ.

(f) SwAV and DeepClusterV2 have minimal inconsistencies in the ranking of MSG* vs PGGAN on CelebaHQ and StyleGAN2* vs SNGAN on Church, but the differences in the absolute values of the FID metric are negligible, so we consider these embedding models as mostly consistent.

Overall, self-supervised embeddings provide a more reasonable FID ranking across existing non-Imagenet benchmarks. For completeness, we also report the FID values for the Imagenet dataset in Table 6. In this case, rankings with all embeddings are the same, which confirms that the SwAV representations can be used for Imagenet as well, while it is not the main focus of our work.

3.2 Precision

The values of the Precision metric are reported in Table 3. The main observations are listed below:

(a) As with FID, all supervised InceptionV3/Resnet50 embeddings provide the same ranking, except minor differences between MSG with truncation and StyleGAN on CelebaHQ, and StyleGAN2 and PGGAN on Church. Self-supervised SwAV and DeepClusterV2 are also consistent except the negligible difference in the ranking of PGGAN and MSG on CelebaHQ and Church;

(b) The most notable inconsistency between supervised and self-supervised embeddings is revealed on the LSUN-Church dataset, where InceptionV3 considers MSG to be comparable to StyleGAN2, while SwAV ranks StyleGAN2 significantly higher. To analyze which ranking of two GANs is more seasonable, we perform the following. On the synthetic data from the first GAN, we train a classifier that aims to distinguish between real and synthetic images. This classifier is then evaluated on the synthetic data from the second GAN. Concretely, we train a classifier to detect synthetic images on real LSUN-Church and the images generated by MSG. Then we evaluate this model on hold-out real images and images produced by StyleGAN2. Intuitively, if a model was trained on high-quality synthetic samples, it will easily detect lower-quality ones. On the other hand, if the model learns to detect only low-quality synthetics, it will be harder to discriminate real images from the high-quality one. In this experiment, we employ a Resnet50 classifier with a binary cross-entropy loss. The results for the Church dataset are provided in Table 4, meaning that the StyleGAN2 images are of higher quality, therefore, the SwAV ranking is more reasonable. There is also a minor inconsistency in the ranking of StyleGAN and StyleGAN2 on FFHQ, which we consider as negligible.

(c) Imagenet21k ranks GANs less reliably compared to SwAV. The most notable mistake is a ranking of COCO-GAN and PGGAN on Bedroom, where PGGAN produces more visually appealing images, see Figure 3. Another case is comparison on CelebaHQ, where Imagenet21k ranks PGGAN higher that the more powerful MSG, see samples in Section B.

Table 4: The accuracy of fake images detection on Church. The rows correspond to GANs producing the train synthetics, while the columns correspond to GANs producing the test.

Train/Test	**MSG**	**StyleGAN2**
MSG	0.999	0.610
StyleGAN2	0.967	0.979

3.3 RECALL

The values of the Recall metric are shown in Table 5, and the main observations are provided below:

(a) As in previous experiments, there are only minor inconsistencies between supervised InceptionV3 and Resnet50 models, namely, StyleGAN vs COCO-GAN on the Bedroom dataset and MSG vs PGGAN on the Church dataset. The only insignificant difference between the self-supervised methods is the ranking of StyleGAN with truncation vs SNGAN on the Church dataset, however, Recall values for both models are negligible. In terms of recall, Imagenet21k ranking always coincides with the ranking obtained by self-supervised methods, except the negligible discrepancy between MSG and PGGAN on the Church dataset;

(b) The absolute Recall values for SwAV/DeepClusterV2 are smaller compared to InceptionV3/Resnet50. We attribute this behavior to the fact that GANs tend to simplify images omitting the details (Bau et al., 2019), e.g. people in front of buildings, cars, fences, etc. The classifier-pretrained embeddings are less sensitive to these details, since they are not crucial for correct classification. In contrast, self-supervised embeddings are more susceptible to small details (see Figure 2 and Table 4), hence, more images are considered "not covered". Figure 5 in Section C shows examples of real LSUN-Church images that are "definitely covered" by StyleGAN2 from the standpoint of InceptionV3 embeddings, but are "not covered" if SwAV embeddings are used. More formally, we say that a real image is covered by a synthetic one with the neighborhood size k, if the distance between their embeddings does not exceed the distance from the embedding of the synthetic image to its k-th nearest neighbor in the set of all synthetic embeddings. The images from Figure 5 are covered by at least 10 synthetic images with neighborhood size 5 with InceptionV3 embeddings, while being not covered even by the neighborhood of size 100 for SwAV embeddings. These images possess many small details, such as monuments, cars, people, branches in the foreground, and so on, that GANs usually omit to generate.

Table 6: FID values for GANs on Imagenet.

	IMAGENET			
InceptionV3	BigGAN-deep	BigGAN	S3GAN	YLG
	7.568	8.175	12.005	21.766
Resnet50	BigGAN-deep	BigGAN	S3GAN	YLG
	12.495	20.616	22.330	36.342
Imagenet21k	BigGAN-deep	BigGAN	S3GAN	YLG
	355.7	625.3	1214	1701
SwAV	BigGAN-deep	BigGAN	S3GAN	YLG
	2.332	4.032	4.191	5.912
DeepClusterV2	BigGAN-deep	BigGAN	S3GAN	YLG
	3.876	6.011	6.512	9.073

Table 5: Recall values for different GAN and embedding models. The '*' symbol indicates models with truncation. Inconsistencies between InceptionV3 and SwAV models are highlighted in color. To calculate Recall, we use the neighborhood size $k = 5$.

	CELEBAHQ				FFHQ			
InceptionV3	MSG 0.477	PGGAN 0.398	StyleGAN 0.281	MSG* 0.276	StyleGAN2 0.632	MSG 0.538	StyleGAN 0.474	MSG* 0.339
Resnet50	MSG 0.502	PGGAN 0.330	StyleGAN 0.284	MSG* 0.277	StyleGAN2 0.624	MSG 0.547	StyleGAN 0.456	MSG* 0.299
Imagenet21k	MSG 0.546	MSG* 0.321	StyleGAN 0.315	PGGAN 0.287	StyleGAN2 0.688	MSG 0.551	StyleGAN 0.452	MSG* 0.335
SwAV	MSG 0.151	MSG* 0.055	StyleGAN 0.035	PGGAN 0.027	StyleGAN2 0.399	MSG 0.193	StyleGAN 0.095	MSG* 0.063
DeepClusterV2	MSG 0.185	MSG* 0.074	StyleGAN 0.042	PGGAN 0.039	StyleGAN2 0.409	MSG 0.220	StyleGAN 0.132	MSG* 0.078

	LSUN-BEDROOM				
InceptionV3	PGGAN 0.516	COCO-GAN 0.476	StyleGAN 0.397	RPGAN 0.190	RPGAN div. 0.110
Resnet50	PGGAN 0.352	StyleGAN 0.304	COCO-GAN 0.258	RPGAN 0.058	RPGAN div. 0.030
Imagenet21k	StyleGAN 0.293	PGGAN 0.240	COCO-GAN 0.157	RPGAN 0.008	RPGAN div. 0.003
SwAV	StyleGAN 0.069	PGGAN 0.015	COCO-GAN 0.003	RPGAN 0.0003	RPGAN div. 0.00003
DeepClusterV2	StyleGAN 0.109	PGGAN 0.039	COCO-GAN 0.009	RPGAN 0.001	RPGAN div. 0.0

	LSUN-CHURCH					
InceptionV3	StyleGAN2 0.519	MSG 0.491	PGGAN 0.461	MSG* 0.271	SNGAN 0.090	StyleGAN2* 0.071
Resnet50	StyleGAN2 0.460	PGGAN 0.413	MSG 0.406	MSG* 0.182	SNGAN 0.038	StyleGAN2* 0.021
Imagenet21k	StyleGAN2 0.350	MSG 0.260	PGGAN 0.251	MSG* 0.105	StyleGAN2* 0.013	SNGAN 0.010
SwAV	StyleGAN2 0.073	PGGAN 0.019	MSG 0.008	MSG* 0.002	StyleGAN2* 0.0014	SNGAN 0.0002
DeepClusterV2	StyleGAN2 0.112	PGGAN 0.058	MSG 0.031	MSG* 0.009	SNGAN 0.002	StyleGAN2* 0.002

(c) Interestingly, the Precision values for SwAV are quite high, therefore, SwAV considers the state-of-the-art generative models being able to produce high-fidelity images, but failing to generate diverse images with small details.

(d) There are two significant inconsistencies in rankings based on InceptionV3 and SwAV. First, on CelebaHQ, SwAV prefers MSG* over PGGAN. Second, on LSUN-Bedroom, InceptionV3 ranks PGGAN higher than StyleGAN. Since StyleGAN is a more powerful model compared to PGGAN, we also consider it as a case of more reliable ranking with SwAV, even though it is difficult to confirm quantitatively due to the lack of an "oracle" measure of generation diversity.

4 Conclusion

In this paper, we have investigated if the state-of-the-art self-supervised models can produce more appropriate representations for GAN evaluation. With extensive experiments, we have shown that using these representations often corrects the cases of misleading ranking obtained with classification-pretrained embeddings. Overall, self-supervised representations provide more adequate GAN comparison on the four established non-Imagenet benchmarks of natural images. Of course, we do not claim that they should be used universally for all areas, e.g. for spectrograms or medical images. But our work indicates that obtaining good representations needed for proper GAN evaluation does not require supervision, therefore, domain-specific self-supervised learning becomes a promising direction for further study.

REFERENCES

Shane Barratt and Rishi Sharma. A note on the inception score. *arXiv preprint arXiv:1801.01973*, 2018.

David Bau, Jun-Yan Zhu, Jonas Wulff, William Peebles, Hendrik Strobelt, Bolei Zhou, and Antonio Torralba. Seeing what a gan cannot generate. In *Proceedings of the IEEE International Conference on Computer Vision*, pp. 4502–4511, 2019.

Ali Borji. Pros and cons of gan evaluation measures. *Computer Vision and Image Understanding*, 179:41–65, 2019.

Andrew Brock, Jeff Donahue, and Karen Simonyan. Large scale GAN training for high fidelity natural image synthesis. In *International Conference on Learning Representations*, 2019. URL `https://openreview.net/forum?id=B1xsqj09Fm`.

Mathilde Caron, Ishan Misra, Julien Mairal, Priya Goyal, Piotr Bojanowski, and Armand Joulin. Unsupervised learning of visual features by contrasting cluster assignments. *arXiv preprint arXiv:2006.09882*, 2020.

Ting Chen, Simon Kornblith, Mohammad Norouzi, and Geoffrey Hinton. A simple framework for contrastive learning of visual representations. *arXiv preprint arXiv:2002.05709*, 2020.

Giannis Daras, Augustus Odena, Han Zhang, and Alexandros G Dimakis. Your local gan: Designing two dimensional local attention mechanisms for generative models. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 14531–14539, 2020.

J. Deng, W. Dong, R. Socher, L.-J. Li, K. Li, and L. Fei-Fei. ImageNet: A Large-Scale Hierarchical Image Database. In *CVPR09*, 2009.

D.C. Dowson and B.V. Landau. The fréchet distance between multivariate normal distributions. *Journal of multivariate analysis*, 12(3):450–455, 1982.

Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pp. 770–778, 2016.

Kaiming He, Haoqi Fan, Yuxin Wu, Saining Xie, and Ross Girshick. Momentum contrast for unsupervised visual representation learning. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 9729–9738, 2020.

Dan Hendrycks, Mantas Mazeika, Saurav Kadavath, and Dawn Song. Using self-supervised learning can improve model robustness and uncertainty. In *Advances in Neural Information Processing Systems*, pp. 15663–15674, 2019.

Martin Heusel, Hubert Ramsauer, Thomas Unterthiner, Bernhard Nessler, and Sepp Hochreiter. Gans trained by a two time-scale update rule converge to a local nash equilibrium. In *Advances in Neural Information Processing Systems*, pp. 6626–6637, 2017.

Animesh Karnewar and Oliver Wang. Msg-gan: Multi-scale gradients for generative adversarial networks. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 7799–7808, 2020.

Tero Karras, Timo Aila, Samuli Laine, and Jaakko Lehtinen. Progressive growing of gans for improved quality, stability, and variation. *arXiv preprint arXiv:1710.10196*, 2017.

Tero Karras, Samuli Laine, and Timo Aila. A style-based generator architecture for generative adversarial networks. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, pp. 4401–4410, 2019a.

Tero Karras, Samuli Laine, Miika Aittala, Janne Hellsten, Jaakko Lehtinen, and Timo Aila. Analyzing and improving the image quality of stylegan. *arXiv preprint arXiv:1912.04958*, 2019b.

Alexander Kolesnikov, Lucas Beyer, Xiaohua Zhai, Joan Puigcerver, Jessica Yung, Sylvain Gelly, and Neil Houlsby. Big transfer (bit): General visual representation learning. *arXiv preprint arXiv:1912.11370*, 2019.

Tuomas Kynkäänniemi, Tero Karras, Samuli Laine, Jaakko Lehtinen, and Timo Aila. Improved precision and recall metric for assessing generative models. In *Advances in Neural Information Processing Systems*, pp. 3929–3938, 2019.

Chieh Hubert Lin, Chia-Che Chang, Yu-Sheng Chen, Da-Cheng Juan, Wei Wei, and Hwann-Tzong Chen. COCO-GAN: generation by parts via conditional coordinating. In *IEEE International Conference on Computer Vision (ICCV)*, 2019.

Ziwei Liu, Ping Luo, Xiaogang Wang, and Xiaoou Tang. Large-scale celebfaces attributes (celeba) dataset. *Retrieved August*, 15:2018, 2018.

Mario Lucic, Michael Tschannen, Marvin Ritter, Xiaohua Zhai, Olivier Bachem, and Sylvain Gelly. High-fidelity image generation with fewer labels. *arXiv preprint arXiv:1903.02271*, 2019.

Takeru Miyato, Toshiki Kataoka, Masanori Koyama, and Yuichi Yoshida. Spectral normalization for generative adversarial networks. In *International Conference on Learning Representations*, 2018. URL `https://openreview.net/forum?id=B1QRgziT-`.

Muhammad Ferjad Naeem, Seong Joon Oh, Youngjung Uh, Yunjey Choi, and Jaejun Yoo. Reliable fidelity and diversity metrics for generative models. *arXiv preprint arXiv:2002.09797*, 2020.

Stanislav Pidhorskyi, Donald A Adjeroh, and Gianfranco Doretto. Adversarial latent autoencoders. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 14104–14113, 2020.

Robin Rombach, Patrick Esser, and Björn Ommer. Making sense of cnns: Interpreting deep representations & their invariances with inns. *arXiv preprint arXiv:2008.01777*, 2020.

Mihaela Rosca, Balaji Lakshminarayanan, David Warde-Farley, and Shakir Mohamed. Variational approaches for auto-encoding generative adversarial networks. *arXiv preprint arXiv:1706.04987*, 2017.

Mehdi SM Sajjadi, Olivier Bachem, Mario Lucic, Olivier Bousquet, and Sylvain Gelly. Assessing generative models via precision and recall. In *Advances in Neural Information Processing Systems*, pp. 5228–5237, 2018.

Tim Salimans, Ian Goodfellow, Wojciech Zaremba, Vicki Cheung, Alec Radford, and Xi Chen. Improved techniques for training gans. In *Advances in neural information processing systems*, pp. 2234–2242, 2016.

Christian Szegedy, Vincent Vanhoucke, Sergey Ioffe, Jon Shlens, and Zbigniew Wojna. Rethinking the inception architecture for computer vision. In *Proceedings of the IEEE conference on computer vision and pattern recognition*, pp. 2818–2826, 2016.

Andrey Voynov and Artem Babenko. Rpgan: Gans interpretability via random routing. *arXiv preprint arXiv:1912.10920*, 2019.

Qiantong Xu, Gao Huang, Yang Yuan, Chuan Guo, Yu Sun, Felix Wu, and Kilian Weinberger. An empirical study on evaluation metrics of generative adversarial networks. *arXiv preprint arXiv:1806.07755*, 2018.

Fisher Yu, Ari Seff, Yinda Zhang, Shuran Song, Thomas Funkhouser, and Jianxiong Xiao. Lsun: Construction of a large-scale image dataset using deep learning with humans in the loop. *arXiv preprint arXiv:1506.03365*, 2015.

Sharon Zhou, Mitchell Gordon, Ranjay Krishna, Austin Narcomey, Li F Fei-Fei, and Michael Bernstein. Hype: A benchmark for human eye perceptual evaluation of generative models. In *Advances in Neural Information Processing Systems*, pp. 3449–3461, 2019.

A APPENDIX

A.1 THE DETAILS OF THE VISUALIZATION TECHNIQUE IN SECTION 3.1

The technique from Rombach et al. (2020) proposes to construct the embedding visualization in the following way. Let us have an autoencoder $A(x)$, whose latent representations are denoted by z. It is assumed that a latent representation $z{=}A(x)$ captures all the information from the image x, since the autoencoder's goal it to fully reconstruct x from z. Let us denote the embedding model we want to study by $E(x)$. For a particular image x, Rombach et al. (2020) compute an autoencoder representation $z = A(x)$ and aims to disentangle the information contained in the autoencoder representation z into the information contained in the image embedding $e = E(x)$ and the information v to which the embedding model $E(x)$ is invariant. To this end, an invertible neural network (INN) is trained, which predicts the invariant part $v = \text{INN}(z, e)$ based on the autoencoder representation and embedding. Moreover, it is trained in such a way that the invariant part has a normal distribution $v \sim \mathcal{N}(0, 1)$. Finally, a bunch of images, having the same e but different invariant parts v are produced. Namely, several samples of invariant parts $\widehat{v}$ are produced from $\mathcal{N}(0, 1)$ and the corrseponding latent representations are computed from $\widehat{v}$ and embedding e, that is $\widehat{z} = \text{INN.reverse}(v, e)$. Then $\widehat{z}$ can be decoded into an image using the autoencoder. As a result, for a given embedding model $E(x)$ and a given image x it allows to obtain a set of images with approximately the same embeddings, but varying invariant part. For the CelebaHQ dataset, we use ALAE autoencoder (Pidhorskyi et al., 2020) and train INN with the hyperparameters provided in (Rombach et al., 2020).

B CELEBAHQ SAMPLES

Figure 4: Random sample of images generated by MSG without truncation and PGGAN trained on CelebaHQ dataset. One can see that the quality of images generated by MSG is substantially higher.

C CHURCH IMAGES

Figure 5: Examples of real images that are confidently covered by StyleGANv2 in terms of InceptionV3 embeddings, but not covered in terms of SwAV.

D THE EMBEDDING MODELS CHECKPOINTS USED IN OUR STUDY

Representation	Dim	URL	Checkpoint
InceptionV3	2048	https://github.com/mseitzer/pytorch-fid	https://github.com/mseitzer/pytorch-fid/releases/download/fid_weights/pt_inception-2015-12-05-6726825d.pth
Resnet-50	2048	https://pytorch.org/docs/stable/torchvision/models.html	https://download.pytorch.org/models/resnet50-19c8e357.pth
Imagenet21k	2048	https://tfhub.dev/google/bit/m-r50x1/1	https://tfhub.dev/google/bit/m-r50x1/1
SwAV	2048	https://github.com/facebookresearch/swav	https://dl.fbaipublicfiles.com/deepcluster/swav_800ep_pretrain.pth.tar
DeepClusterV2	2048	https://github.com/facebookresearch/swav	https://dl.fbaipublicfiles.com/deepcluster/deepclusterv2_800ep_pretrain.pth.tar

Table 7: The URLs with checkpoints used in our experiments.