Deep Photo Enhancer: Unpaired Learning for Image Enhancement from Photographs with GANs

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Abstract

This paper proposes an unpaired learning method for image enhancement. Given a set of photographs with the desired characteristics, the proposed method learns a photo enhancer which transforms an input image into an enhanced image with those characteristics. The method is based on the framework of two-way generative adversarial networks (GANs) with several improvements. First, we augment the U-Net with global features and show that it is more effective. The global U-Net acts as the generator in our GAN model. Second, we improve Wasserstein GAN (WGAN) with an adaptive weighting scheme. With this scheme, training converges faster and better, and is less sensitive to parameters than WGAN-GP. Finally, we propose to use individual batch normalization layers for generators in two-way GANs. It helps generators better adapt to their own input distributions. All together, they significantly improve the stability of GAN training for our application. Both quantitative and visual results show that the proposed method is effective for enhancing images.

1. Introduction

Photographs record valuable moments of our life. With the popularization of mobile phone cameras, users enjoy taking photographs even more. However, current cameras have limitations. They have to reconstruct a complete and high-quality image from a set incomplete and imperfect samples of the scene. The samples are often noisy, incomplete in color and limited in the resolution and the dynamic range. In addition, the camera sensor responds linearly to the incoming light while human perception performs more sophisticated non-linear mapping. Thus, users could be disappointed with photographs they take because the photographs do not match their expectations and visual experience. The problem is even aggravated for mobile cameras because of their small sensors and compact lenses.

Image enhancement methods attempt to address the issues with color rendition and image sharpness. There are interactive tools and semi-automatic methods for this purpose. Most interactive software provides elementary tools such as histogram equalization, sharpening, contrast adjustment and color mapping, and some advanced functions such as local and adaptive adjustments. The quality of the results however highly depends on skills and aesthetic judgement of the users. In addition, it often takes a significant amount of time to reach satisfactory retouching results. The semi-automatic methods facilitate the process by only requiring adjustments of a few parameters. However, the results could be very sensitive to parameters. In addition, these methods are often based on some heuristic rules about human perception such as enhancing details or stretching contrast. Thus, they could be brittle and lead to bad results.

This paper proposes a method for image enhancement by learning from photographs. The method only requires a set of “good” photographs as the input. They have the characteristics that the user would like to have for their photographs. They can be collected easily from websites or any stock of photographs. We treat the image enhancement problem as an image-to-image translation problem in which an input image is transformed into an enhanced image with the characteristics embedded in the set of training photographs. Thus, we tackle the problem with a two-way GAN whose structure is similar to CycleGAN [26]. However, GANs are notorious for their instability. For addressing the issue and obtaining high-quality results, we propose a few improvements along the way of constructing our two-way GAN. First, for the design of the generator, we augment the U-Net [20] with global features. The global features capture the notion of scene setting, global lighting condition or even subject types. They are helpful for determining what local operations should be performed. Second, we propose an adaptive weighting scheme for Wasserstein...
GAN (WGAN) [1]. WGAN uses weight clipping for enforcing the Lipschitz constraint. It was later discovered a terrible way and some proposed to use the gradient penalty for enforcing the constraint [9]. However, we found that the approach is very sensitive to the weighting parameter of the penalty. Thus, we propose to use an adaptive weighting scheme to improve the convergence of WGAN training. Finally, most two-way GAN architectures use the same generator in both forward and backward passes. It makes sense since the generators in both paths perform similar mapping with the same input and output domains. However, we found that, although in the same domain, the inputs actually come from different sources, one from the input data and the other from the generated data. The discrepancy between distributions of input sources could have vicious effects on the performance of the generator. We propose to use individual batch normalization layers for the same type of generators. This way, the generator can adapt better to the input data distribution. With these improvements, our method can provide high-quality enhanced photographs with better color rendition and sharpness. The results often look more natural than previous methods. In addition, the proposed techniques, global U-Net, adaptive WGAN and individual batch normalization, can be useful for other applications.

2. Related work

Image enhancement has been studied for a long time. Many operations and filters have been proposed to enhance details, improve contrast and adjust colors. Wang et al. [22] proposed a method for enhancing details while preserving naturalness. Aubry et al. [2] proposed local Laplacian operator for enhancing details. Most of these operations are algorithmic and based on heuristic rules. Bychkovsky et al. [4] proposed a learning-based regression method for approximating photographers' adjustment skills. For this purpose, they collected a dataset containing images before and after adjustments by photographers.

The convolutional neural networks (CNNs) have become a major workhorse for a wide set of computer vision and image processing problems. They have also been applied to the image enhancement problem. Yan et al. [23] proposed the first deep-learning-based method for photo adjustment. Gharbi et al. [7] proposed a fast approximation for existing filters. Ignatov et al. [10] took a different approach by learning the mapping between a mobile phone camera and a DSLR camera. They collected the DPED dataset consisting of images of the same scene taken by different cameras. A GAN model was used for learning the mapping. Chen et al. [6] approximated existing filters using a fully convolutional network. It can only learn existing filters and cannot do beyond what they can do. All these methods are supervised and require paired images while ours is unpaired. The unpaired nature eases the process of collecting training data.

Our method is based on the generative adversarial networks (GANs) [8]. Although GANs have been proved powerful, they are notorious on training instability. Significant efforts have been made toward stable training of GANs. Wasserstein GAN uses the earth mover distance to measure the distance between the data distribution and the model distribution and significantly improves training stability [1]. Gulrajani et al. found that WGAN could still generate low-quality samples or fail to converge due to weight clipping [9]. Instead of weight clipping, they proposed to penalize the norm of the gradient of the discriminator with respect to the input. The resultant model is called WGAN-GP (WGAN with gradient penalty). It often generates higher-quality samples and converges faster than WGAN. There are also energy-based GAN variants, such as BEGAN [3] and EBGAN [25].

Isola et al. proposed a conditional adversarial network as a general-purpose solution to image-to-image translation problems [13], converting from one representation of a scene to another, such as from a semantic label map to a realistic image or from a day image to its night counterpart. Although generating amazing results, their method requires paired images for training. Two-way GANs were later proposed for addressing the problem by introducing cycle consistency. Famous two-way GANs include CycleGAN [26], DualGAN [24] and DISCOGAN [14]. We formulate image enhancement as an instance of the image-to-image translation problems and solve it with a two-way GAN.

3. Overview

Our goal is to obtain a photo enhancer $\Phi$ which takes an input image $x$ and generates an output image $\Phi(x)$ as the enhanced version of $x$. It is however not easy to define enhancement clearly because human perception is complicated and subjective. Instead of formulating the problem using a set of heuristic rules such as “details should be enhanced” or “contrast should be stretched”, we define enhancement by a set of examples $Y$. That is, we ask the user to provide a set of photographs with the characteristics he/she would like to have. The proposed method aims at discovering the common characteristics of the images in $Y$ and deriving the enhancer so that the enhanced image $\Phi(x)$ shares these characteristics while still resembling the original image $x$ in content.

Because of its nature with set-level supervision, the problem can be naturally formulated using the framework of GANs which learns the embedding of the input samples and generates output samples locating within the subspace spanned by training samples. A GAN model often consists of a discriminator $D$ and a generator $G$. The framework has been used for addressing the image-to-image translation problem which transforms an input image from the source domain $X$ to the output image in the target domain $Y$ [13].
In our application, the source domain $X$ represents original images while the target domain $Y$ contains images with the desired characteristics.

Figure 1(a) gives the architecture for 1-way GAN. Given an input $x \in X$, the generator $G_X$ transforms $x$ into $y' = G_X(x) \in Y$. The discriminator $D_Y$ aims at distinguishing between the samples in the target domain $\{y\}$ and the generated samples $\{y' = G_X(x)\}$. To enforce cycle consistency for better results, several have proposed 2-way GANs such as CycleGAN [26] and DualGAN [24]. They require $G_Y(G_X(x)) = x$ where the generator $G_Y$ takes a $G_X$-generated sample and maps it back to the source domain $X$. In addition, 2-way GANs often contain a forward mapping ($X \rightarrow Y$) and a backward mapping ($Y \rightarrow X$). Figure 1(b) shows the architecture of 2-way GANs. In the forward pass, $x \xrightarrow{G_X} y' \xrightarrow{G_Y'} x''$ and we check the consistency between $x$ and $x''$. In the backward pass, $y \xrightarrow{G_Y} x' \xrightarrow{G_X'} y''$ and we check the consistency between $y$ and $y''$.

In the following sections, we will first present the design of our generator (Section 4). Next, we will describe the design of our 1-way GAN (Section 5) and the one for our 2-way GAN (Section 6).

4. Generator

For our application, the generator in the GAN framework plays an important role as it will act as the final photo enhancer $\Phi$. This section proposes a generator and compares it with several options. Figure 2(a) shows the proposed generator. The size of input images is fixed at $512 \times 512$.

Our generator is based on the U-Net [20] which was originally proposed for biomedical image segmentation but later also showed strong performance on many tasks. U-Net however does not perform very well on our task. Our conjecture is that the U-Net does not include global features. Our vision system usually adjusts to the overall lighting conditions and scene settings. Similarly, cameras have scene settings and often apply different types of adjustments depending on the current setting. The global features could reveal high-level information such as the scene category, the subject type or the overall lighting condition which could be useful for individual pixels to determine their local adjustments. Thus, we add the global features into the U-Net.

In order to improve the model efficiency, the extraction of global features shares the same contracting part of the U-Net with the extraction of local features for the first five layers. Each contraction step consists of $5 \times 5$ filtering with stride 2 followed by SELU activation [15] and batch normalization [12]. Given the $32 \times 32 \times 128$ feature map of the 5th layer, for global features, the feature map is further reduced to $16 \times 16 \times 128$ and then $8 \times 8 \times 128$ by performing the aforementioned contraction step. The $8 \times 8 \times 128$ feature map is then reduced to $1 \times 1 \times 128$ by a fully-connected layer followed by a SELU activation layer and then another fully-connected layer. The extracted $1 \times 1 \times 128$ global features are then duplicated $32 \times 32$ copies and concatenated after the $32 \times 32 \times 128$ feature map for the low-level features, resulting a $32 \times 32 \times 256$ feature map which fuses both local and global features together. The expansive path of the U-Net is then performed on the fused feature map. Finally, the idea of residual learning is adopted because it has been shown effective for image processing tasks and helpful on convergence. That is, the generator only learns the difference between the input image and the label image.

Global features have been explored by other image processing tasks such as colorization [11]. However, their model requires an extra supervised network trained with explicit scene labels. For many applications, it is difficult to define labels explicitly. The novelty of our model is to use the U-Net itself to encode an implicit feature vector describing global features useful for the target application.

The dataset. We used the MIT-Adobe 5K dataset [4] for training and testing. The dataset contains 5,000 images, each of which was retouched by five well-trained photographers using global and local adjustments. We selected the results of photographer C as labels since he was ranked the highest in the user study [4]. The dataset was split into three partitions: the first one consists of 2,250 images and their retouched versions were used for training in the supervised setting in this section; for the unpaired training in Section 5 and Section 6, the retouched images of another 2,250 images acted as the target domain while the 2,250 images of the first partition were used for the source domain; the rest 500 images were used for testing in either setting.

The experiments. We evaluated several network architectures for the generator. (1) DPED [10]: since we only evaluate on generators, we took only the generator of their GAN architecture. (2) 8RESBLK [26, 17]: the generator has been used in CycleGAN [26] and UNIT [17]. (3) FCN [6]: a fully convolutional network for approximating filters. (4) CRN [5]: the architecture has been used to synthesize realistic images from semantic labels. (5) U-Net [20]. The residual learning is augmented to all of them. Because of the image size and the limitation on memory capacity, the
number of features of the first layer is limited at 16. Otherwise, the overall architecture cannot be fitted within the memory. The loss function is to maximize PSNR:

$$\arg \min_{G_X} \mathbb{E}_{y,y'} \left[ \log_{10}(MSE(y, y')) \right],$$

where

$$MSE(x, y) = \frac{1}{mn} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} \|x(i,j) - y(i,j)\|^2.$$  

Table 1 shows both the average PSNR and SSIM values for all compared architectures on approximating fast local Laplacian filtering for the 500 testing images from MIT-Adobe 5K dataset. By adding the global features, the proposed architecture provides nearly 3dB gain over its counterpart without global features, and outperforms all compared architectures. Our generator does an excellent job on approximating the fast local Laplacian filter with 33.93dB PSNR, better than FCN which is designed for such tasks.

Table 2 reports the performance of these architectures on predicting the retouched images by photographers on the MIT-Adobe 5K dataset. By adding the global features, the proposed architecture provides nearly 3dB gain over its counterpart without global features, and outperforms all compared architectures. The average accuracy of different network architectures on approximating fast local Laplacian filtering on the MIT-Adobe 5K dataset is reported in Table 3.

### 5. One-way GAN

This section presents our GAN architecture for unpaired training. Figure 2(b) illustrates the architecture of our discriminator. By employing the generator (Figure 2(a)) as $G_X$ and the discriminator (Figure 2(b)) as $D_Y$ in Figure 1(a), we have the architecture for our 1-way GAN. As mentioned in Section 4, for training GANs, to avoid the content correlation between the source and the target domains, we used 2,250 images of the MIT-Adobe 5K dataset as the source domain while using the retouched images of another 2,250 images as the target domain.

There are many variants of GAN formulations. We first experimented with several flavors of GANs, including GAN [8], LSGAN [18], DRAGAN [16] and WGAN-GP [9], with different parameter settings. Table 3 reports the results for some of them. All GANs require the parameter $\alpha$ for the weight of the identity loss $\mathbb{E}_{x,y'} \left[ MSE(x, y') \right]$ which ensures the output is similar to the input. The parameter $D/G$ represents the ratio between the numbers of discriminator and generator training passes. In our application, WGAN-GP performs better than GAN, LSGAN and DRAGAN. Table 3 only reports the best performance for methods other than WGAN-GP. However, the performance of WGAN-GP depends on an additional parameter $\lambda$ which weights the gradient penalty.

WGAN relies on the Lipschitz constraint on the training objective: a differentiable function is 1-Lipschtiz if and only if it has gradients with norm at most 1 everywhere [9]. For satisfying the constraint, WGAN-GP directly constrains the gradient norm of the discriminator output with respect to its input by adding the following gradient penalty,

$$\mathbb{E}_{y} \left[ (\|\nabla_y D_Y(\hat{y})\|_2 - 1)^2 \right],$$

where $\hat{y}$ is point sampled along straight lines between points.
in the target distribution and the generator distribution. A parameter $\lambda$ weights the penalty with the original discriminator loss. $\lambda$ determines the tendency that gradients approaches 1. If $\lambda$ is too small, the Lipschitz constraint cannot be guaranteed. On the other hand, if $\lambda$ is too large, the convergence could be slow as the penalty could over-weight the discriminator loss. It makes the choice of $\lambda$ important. Instead, we use the following gradient penalty,

$$\mathbb{E}_{\hat{y}} \left[ \max(0, \| \nabla_{\hat{y}} D_Y(\hat{y}) \|_2 - 1) \right], \quad (4)$$

which better reflects the Lipschitz that requires the gradients are less than or equal to 1 and only penalizes the part which is larger than 1. More importantly, we employ an adaptive weighting scheme for adjusting the weight $\lambda$, which chooses a proper weight so that the gradients locate within a desired interval, say $[1.001, 1.05]$. If the moving average of gradients within a sliding window (size=50) is larger than the upper bound, it means that the current weight $\lambda$ is too small and the penalty is not strong enough to ensure the Lipschitz constraint. Thus, we increase $\lambda$ by doubling the weight. On the other hand, if the moving average is smaller than the lower bound, we decay $\lambda$ into a half so that it will not become too large.

Figure 3 compares WGAN-GP and the proposed A-WGAN (Adaptive WGAN) on the swissroll dataset. It is clear that the proposed adaptive weighting WGAN converges to the target distribution regardless of the initial setting of $\lambda$ while the results of WGAN-GP significantly depend on $\lambda$. Table 3 also confirms that A-WGAN outperforms WGAN-GP and achieves the best performance among compared GANs. Note that the PSNR value is not very high even with A-WGAN. It is impossible to capture the exact mapping since the photographer can be subjective with different tastes and often inconsistent. The best that a method can do is to discover the common trend on image characteristics from the training data. However, even if we cannot accurately predict human labels, the learned operation can still improve image quality as shown in Section 7.

6. Two-way GAN

Section 5 has determined to use A-WGAN as our GAN formulation. For achieving better results, this section extends the GAN architecture into a 2-way GAN. Figure 1(b) shows the architecture for the 2-way GAN. Table 4 compares WGAN-GP and the proposed A-WGAN when extending to the 2-way GAN architectures. Both have gains from the use of the 2-way GAN architecture. However, the gain is more significant on WGAN-GP. It could be because there is less room for A-WGAN to improve.

Most 2-way GANs use the same generator for both $G_X$ and $G'_X$ because both map an input from the domain $X$ to the domain $Y$, and similarly for $G_Y$ and $G'_Y$. However, from Figure 1(b), the input of $G_X$ is taken from the input samples $X$ while $G'_X$ takes the generated samples $X'$ as its inputs. They could have different distribution characteristics. Thus, it is better that the generators $G_X$ and $G'_X$ adapt to their own inputs. Our solution is to use individual batch normalization (iBN) layers for $G_X$ and $G'_X$. That is, our generators $G_X$ and $G'_X$ share all layers and parameters except for the batch normalization layers. Each generator has its own batch normalization so that it better adapts to the characteristics of its own inputs. Table 4 confirms that the use of individual batch normalization helps the generator adapt to input distributions. With iBN, both WGAN-GP...
and A-WGAN were improved, by 0.31dB and 0.16dB respectively. As shown in Figure 4 and Figure 5, without iBN, the 2-way GAN could fail to capture the right distribution on more challenging cases.

To sum up, our objective consists of several losses. The first one is the identity mapping loss $I$ which requires that the content of the transformed image $y$ should be similar to the input image $x$. Because of the 2-way GAN, there is also a counterpart for mapping from $y$ to $x'$.

$$I = \mathbb{E}_{x,y'}[\text{MSE}(x,y')] + \mathbb{E}_{y,x'}[\text{MSE}(y,x')] .$$

(5)

The second loss is the cycle consistency loss $C$ defined as

$$C = \mathbb{E}_{x,x''}[\text{MSE}(x,x'')] + \mathbb{E}_{y,y''}[\text{MSE}(y,y'')] .$$

(6)

The adversarial losses for the discriminator $A_D$ and the generator $A_G$ are defined as

$$A_D = \mathbb{E}_{x}[D_X(x)] - \mathbb{E}_{x'}[D_X(x')] + \mathbb{E}_{y}[D_Y(y)] - \mathbb{E}_{y'}[D_Y(y')] .$$

(7)

(8)

$$A_G = \mathbb{E}_{x'}[D_X(x') + \mathbb{E}_{y'}[D_Y(y')] .$$

(9)

When training the discriminator, the gradient penalty $P$ is added where

$$P = \mathbb{E}_{\hat{x}}[\max(0, \|\nabla_{\hat{x}} D_X(\hat{x})\|_2 - 1)] + \mathbb{E}_{\hat{y}}[\max(0, \|\nabla_{\hat{y}} D_Y(\hat{y})\|_2 - 1)].$$

(10)

(11)

The term ensures 1-Lipschitz functions for Wasserstein distance. Thus, the discriminator is obtained by the following optimization,

$$\arg \max_{D} [A_D - \lambda P] ,$$

(12)

where the weight $\lambda$ is adaptively adjusted using A-WGAN. The generator is obtained by

$$\arg \min_{G} [-A_G + \alpha I + 10\alpha C] ,$$

(13)

where $\alpha$ weights between the adversarial loss and identity/consistency losses. Finally, we take the resultant generator $G_X$ as the photo enhancer $\Phi$.

7. Results

In addition to training on photographer labels of the MIT-Adobe 5K dataset, we have also collected an HDR dataset
Figure 5 show comparisons on another example. Figure 6 show more comparisons. Again, our HDR model consistently gives the best results. Note that the HDR model trained on HDR images ranked the first and CLHE was the runner-up. When comparing our model with CLHE, 81% of users (323 among 400) preferred our results.

**Limitations.** Our model could amplify noise if the input is very dark and contains a significant amount of noise. In addition, since some HDR images for training are products of tone mapping, our model could suffer from halo artifacts inherited from tone mapping for some images.

**Other applications.** This paper proposes three improve-
input (HDR)

Figure 6. Comparisons of our method with DPED and CLHE. The first and the last inputs were taken by iPhone7+ and Nexus respectively.

Figure 7. Other applications of global U-Net, A-WGAN and iBN.

8. Conclusion

This paper presents Deep Photo Enhancer which learns image enhancement from a set of given photographs with user’s desired characteristics. With its unpaired setting, the process of collecting training images is easy. By taking images provided by different users, the enhancer can be personalized to match individual user’s preference. We have made several technical contributions while searching for the best architecture for the application. We enhance U-Net for image processing by augmenting global features. We improve the stability of WGAN by an adaptive weighting scheme. We also propose to use individual batch normalization layers for generators for improving 2-way GANs.
References


